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HIGH-CURRENT PARTICLE BEAMS: PART I.  
THE WESTERN USSR RESEARCH GROUPS

Simon Kassel, et al

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A continuation of the study of Soviet R&D of high-current, high-energy, charged-particle beams. Analyzes work of four major Soviet research groups engaged in theoretical and experimental study of relativistic electron beams, especially in relation to the collective acceleration mechanism, and application of such beams to (1) plasma and pellet heating, (2) generation of intense microwave oscillations, flash X-rays, and gamma-rays, (3) production of pulsed high pressure in solids, (4) ionospheric sounding, (5) long-distance transmission of particle beams. A large portion of these studies is directed toward solving the problem of controlled thermonuclear reactions by means of plasma containment and inertial heating schemes based on use of high-current relativistic beams. Considerable Soviet effort has also been devoted to exploring means to preserve integrity of beams propagating through neutral gas and plasma, as well as generating microwave emission and laser pumping by electron beams. (See also R-1053, R-1311, R-1333.) 111 pp. Ref. (EP)

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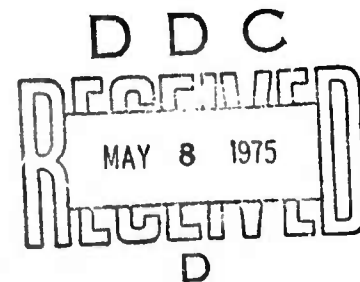
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April 1975

# High-Current Particle Beams

## I. The Western USSR Research Groups

Simon Kassel and Charles D. Hendricks



A Report prepared for

DEFENSE ADVANCED RESEARCH PROJECTS AGENCY



PREFACE

This Report was prepared in the course of a continuing study of Soviet research and development of high-current, high-energy, charged-particle (primarily electron) beams and their applications. That study, in turn, is part of an ongoing program, sponsored by the Defense Advanced Research Projects Agency, which undertakes the systematic coverage of selected areas of Soviet science and technology as reflected in their technical literature. Other reports written by the same authors under this program include: *Soviet Development of Needle-Tip Field-Emission Cathodes for High-Current Electron Beams*, R-1311-ARPA, August 1973; *Soviet Development of Flash X-Ray Machines*, R-1053-ARPA, October 1973; and *Soviet Research and Development of High-Power Gap Switches*, R-1333-ARPA, January 1974.

The material presented here is the result of a detailed analysis of several key R&D groups that are responsible for roughly one-half of the total Soviet effort in this area. The Report thus illuminates a relatively new and significant aspect of Soviet pulsed-power technology; it also demonstrates the considerable momentum and scope of the Soviet effort. It is hoped that the detailed description of the wide-ranging systematic and exhaustive Soviet work reflected in this study will be of interest and, in some cases, of direct help to American researchers working in this area under government-sponsored programs.

SUMMARY

The work of several major Soviet research groups active in the investigation and application of high-current, high-energy, pulsed electron beams is analyzed in detail. The groups are located in the Western USSR at the Kurchatov Institute of Atomic Energy and the Lebedev Physics Institute, both in Moscow, the Physicotechnical Institute in Khar'kov, and the Physicotechnical Institute in Sukhumi. These four research organizations, together with laboratories in Novosibirsk and Tomsk in Siberia, represent the major part of the known Soviet theoretical and experimental facilities devoted to this field in the USSR. The Siberian groups will be the subject of a future Report.

The entire Soviet effort to design high-current, pulsed electron accelerators to study the behavior of electron beams, beam-plasma interaction, the collective process, and the production of ion beams, as well as to apply relativistic particle beams to various areas of science and technology, has been in evidence on a substantial scale since the early sixties and has been showing a steadily increasing growth rate during that period, at least from the viewpoint of the open publications reflecting that effort. On the other hand, the corresponding American effort -- judged solely on the basis of the volume of open publication and the number of authors involved -- has been gathering momentum only since the late sixties and has not yet reached the current Soviet effort levels.

The four groups investigated here are responsible for a large part of the total Soviet research effort in this area and for much of the Soviet achievement so far. The aims of this effort, insofar as explicit statements in the press are concerned, consist of the theoretical and experimental study of relativistic electron beams, especially in relation to the collective acceleration mechanism, and the application of such beams to plasma and pellet heating, the generation of intense microwave oscillations, flash X-rays, and gamma-rays, the production of pulsed high pressure in solids, ionospheric sounding, and long-distance transmission of particle beams. The expected parameters of

the electron beams required to satisfy these aims, as stated by Soviet researchers, range from 10-MeV, 10-MA beams for inertial heating of fusion pellets, through 50-MeV, 1-MA beams for microwave oscillators, to 10-MeV, 1-A beams for ionospheric sounding. As yet, no reports have been published to indicate that any of these aims has been attained, whether in terms of the required input beam power or of the output performance of the application. The known Soviet electron accelerators operate far below these parameters and approximately within the reported range of U.S. machines, with the exception of a few large U.S. accelerators, such as the Aurora, Hermes, and Gamble, which surpass the performances of the Soviet accelerators.

The activity of four research groups shows a fair degree of coordination and what appears to be some division of labor among the groups. Theoretical groups led by L. I. Rudakov (Kurchatov Institute of Atomic Energy), A. A. Rukhadze (Lebedev Physics Institute), and Ya. B. Faynberg (Khar'kov Physicotechnical Institute) have developed a detailed and comprehensive theory of the high-current beam-plasma interaction and the beam neutralization mechanism applicable to a broad range of operating parameters. Thus, specific theoretical, experimentally verified models are presented for nonrelativistic, relativistic, and ultra-relativistic electron beams, with gas pressures ranging from very low to atmospheric, and externally applied magnetic fields of varying intensity. The results of intensive studies of microinstabilities in the beam and in plasma show the feasibility of (1) highly efficient energy transfer in systems consisting of plasma columns within metal guides and (2) transmitting high-current electron beams with varying degrees of energy spread. The use of a plasma-density gradient in the column and of weak-signal modulation of the electron beam as a means of instability control has been examined in detail.

A large proportion of these studies is clearly directed toward the solution of the problem of controlled thermonuclear reactions by means of plasma containment and inertial heating schemes based on the use of high-current relativistic electron beams. However, a considerable amount of work, especially by the Rukhadze and Faynberg groups,

has been directed towards exploring the means of preserving the integrity of the beams propagating through neutral gas and plasma, as well as the generation of microwave emission and laser pumping by electron beams. Rukhadze has developed a broad program of research in microwave oscillators employing electron-beam interaction with gaseous plasma, solid-state plasma, and periodic structures in a vacuum.

Faynberg's contribution to the microwave oscillator program is based on the control of beam-driven plasma instabilities and their frequency bandwidth by means of premodulation of the electron beam.

Also of interest is Faynberg's development of the linear plasma betatron. Both Rukhadze and Faynberg are concerned with novel methods of pumping lasers emitting in the ultraviolet portion of the spectrum. Rukhadze's technique employs exploding wires and is found to be superior to conventional flash lamps in terms of delivered energy and ultraviolet conversion efficiency. Faynberg's use of beam-plasma discharge utilizing the collective interaction effect resulted in stimulated emission observed in a series of wavelengths from several gas species.

The fourth group, headed by A. A. Plyutto at the Physicotechnical Institute in Sukhumi, is the smallest, and its relationship to the overall Soviet pulsed-power effort is peripheral. However, his systematic work with plasma-filled diodes and his development of the first workable collective acceleration mechanism to produce intense electron and proton beams appears promising for the development of high-current, high-energy, particle beam systems.

ACKNOWLEDGMENTS

The authors wish to express their gratitude to Leslie S. Levine of the Naval Research Laboratory and Alan S. Penfold of Telic Corporation for their helpful reviews of this work, and to thank Ihor M. Vitkovitsky of the Naval Research Laboratory and Richard J. Briggs, Laird P. Bradley, and others of the Lawrence Livermore Laboratory for valuable discussions and comments on various technical problems.

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SYMBOLS

$B$	= magnetic field
$c$	= velocity of light in vacuum
$E$	= electron beam energy
$e$	= electron charge
$I$	= beam current
$k$	= wave vector
$L$	= beam length
$\ell$	= discharge gap length
$m$	= electron mass
$n_b$	= beam density
$n_p$	= plasma density
$r$	= beam radius
$T$	= temperature
$V$	= voltage
$v$	= electron beam velocity
$\Delta v$	= linear velocity dispersion
$\gamma$	= $[1-(v/c)^2]^{-1/2}$ = relativistic factor
$\delta$	= instability growth rate
$\nu$	= electron scattering frequency
$\sigma$	= electrical conductivity
$\phi$	= angular velocity dispersion
$\chi$	= thermal conductivity
$\Omega$	= $eH_0/mc$ = gyro or cyclotron (Larmor) frequency
$\omega_L$	= $(4\pi ne^2/m)^{1/2}$ = plasma (Langmuir) frequency



## I. INTRODUCTION

This Report presents a detailed analysis of the work of several outstanding groups of Soviet researchers on the production and study of intense pulsed electron beams. For the past 15 years, Soviet scientific and technical publications have reflected a growing activity in this area, most of which may be categorized as applied science research in beam-plasma interaction problems. At the present time, this activity has reached considerable intensity and scope in terms of the number of technical reports published annually, organizations and personnel directly involved in the work, and the range of related topics under active investigation. There is also evidence of closer coordination among the various institutes than is usual in Soviet practice.

In general terms, the basic goal of this research is high-performance energy conversion in which large energy concentration is allowed to impact on a small volume in a short period of time. In this respect, the electron beam is an alternative to the laser beam as a route to high energy densities.

The obvious requirement for such energy density stems from research on controlled thermonuclear reactions initiated by the inertial method. While this requirement constitutes a major stimulus to the present Soviet work on high-current electron beams, at least as reported in the open-source literature, interest in these beams in connection with fusion research considerably predates the concept of inertial heating. As early as the fifties, relativistic electron beams were studied as a means of heating plasma in fusion reactors, and the basic postulates of current limits and beam stability relating to beam-plasma interaction were set forth.

Another early stimulus to the development of high-current electron beams originated in the area of high-energy physics and, specifically, in attempts to increase the energy and decrease the cost of particle accelerators through the development of the collective acceleration principle first proposed by Veksler.

Both applications are being pursued at this time. However, the experience gained in the course of this research soon generated interest in other areas of application where electron beams could revolutionize the conventional methods and significantly advance the current performance levels. The most important of these applications is in the area called plasma electronics by Soviet scientists. They credit A. I. Akhiezer and Ya. B. Faynberg in the USSR and D. Bohm and E. Gross in the United States with the discovery that microwaves are emitted from plasma exposed to an electron beam. This discovery led to the concept of microwave oscillators and amplifiers based on the interaction of electron beams with plasma or with magnetic fields, capable of high conversion efficiency, narrow bandwidth, and low divergence. These characteristics coupled with high output power would make for superior radar. A relatively large share of current Soviet work in the general area of high-current electron beam research appears to be devoted to microwave plasma oscillators, which are expected eventually to generate  $10^{10}$ -W microwave pulses with conversion efficiency of 10 percent and bandwidth of  $10^{-3}$  to  $10^{-2}$ . In particular, high hopes are attached to the use of ultrarelativistic beams, for which theory predicts very high efficiency and narrow generation line.

Work is also under way in Soviet laboratories on electron beams as pump sources for lasers. The application of electron beams for this purpose is expected to increase the efficiency, spectral range, and variety of available active media.

Each of the above applications of high-current electron beams is represented by a sequence of research reports more or less explicitly dedicated to the given application and reflecting a continuity of active research in that area. There are also some other goals of this research that, while officially announced in various statements by research leaders, are explicitly mentioned in very few or in none of the actual research reports.

In the category of work on which few explicit papers are published is ionospheric sounding by electron beams. This goal, usually referred to together with the production of artificial auroras, requires

the delivery of relatively large energies supplied by electron accelerators aboard space vehicles. It appears as one reason for the evident Soviet stress on minimizing the size of electron beam accelerators for a given beam energy and for the theoretical work on beams in atmospheric gas. It may also be the subject of numerous references in the Soviet statements of research aims to the "transmission of electron beam energy over long distance." Only one instance of an actual Soviet experiment with artificial auroras has been found so far. *Kazakhstanskaya Pravda*, on June 27, 1973 (p.3) described an event code-named *Zarnitsa*, performed by the Institute of Terrestrial Magnetism, Ionosphere, and Radiowave Propagation, Academy of Sciences, USSR, which had taken place on the night of May 29-30, 1973. An electron accelerator aboard an MR-12 meteorological rocket, at an altitude of 100 km, injected a 9-kV, 0.5-A pulse along the geomagnetic lines. These beam parameters are, however, much lower than those discussed by Soviet researchers in connection with ionospheric sounding.

Little information is available on another major research aim included in Soviet lists, i.e., production of flash X-rays. According to Soviet statements, ultrarelativistic electron beams can convert 1 percent of their energy into X-ray beams whose power can reach  $10^{12}$  W with a divergence of  $1^\circ$ . Injection of such high-power X-ray beams into dense gases may produce stimulated X-ray emission.

Intense nuclear reactions can be obtained by exposing light nuclei to electron beams. Neutron sources pumped by high-current relativistic electron beams can realistically be expected to yield up to  $10^{16}$  to  $10^{17}$  neutrons per pulse, exceeding by an order of magnitude the pulsed neutron output of any currently available neutron source.

Finally, the lists of Soviet research aims mention the area of high pressures. Relativistic electron beams can exert megabar pulse pressures in solids at relatively low temperatures. Soviet scientists consider this a means of investigating the feasibility of producing metallic hydrogen.

The energy requirements imposed on the electron beams to meet some of these goals as specified by Soviet writers can be summarized as follows:

Table 1

## EXPECTED ELECTRON BEAM PARAMETERS FOR VARIOUS APPLICATIONS

Application	Energy, MeV	Current, kA	Pulse length, nsec	Remarks
Inertial heating CTR	10	$10^4$	30	focus: $0.3 \text{ cm}^2$
Collective acceleration	10	$10^3$		1-GeV, 10-A ions
Microwave oscillators	50	$10^3$		10% efficiency
Flash X-rays	30	$10^4$		1% efficiency
High pressure	5	30	100	
Ionospheric sounding	10	$10^{-3}$	$10^9$	

The open-source literature to date has not revealed the existence of any Soviet operating accelerators capable of meeting the above requirements, with the exception, perhaps, of those for high-pressure research. While the energy-per-particle and current specifications for ionospheric sounding may appear reasonable in view of the available equipment, the insistence on 1-sec pulses throws the total requirement for energy per pulse beyond the currently available means. In spite of this apparent lack of large machines, however, A. A. Rukhadze, one of the leading Soviet researchers in this area, considers the requirements listed in Table 1 for controlled thermonuclear reactions (CTR) and microwave oscillators as "entirely within the current state of the art" [1].

A number of known Soviet electron beam accelerators were built specifically for this research. High-current electron beams are made of conceptually simple components. A generator charges a transmission line to a high voltage. A triggered gap switch connects the line to a low-impedance field-emission diode, which emits a pulse of electrons with a duration in the nsec range. These electrons are accelerated from the

cathode to a thin metal-foil anode through which the beam passes into a drift tube. Most U.S. and Soviet machines use a Marx generator followed by a Blumlein transmission line. Table 2 describes several Soviet accelerators known from open-source Soviet publications.

The array of experimental equipment listed in Table 2 should not be regarded as indicative of the actual scope or state of the art of Soviet research. It is by no means clear that Soviet laboratories do not have other, more powerful machines, comparable to the Aurora, Hermes, and Gamble accelerators developed in the United States and known to Soviet researchers. It is also possible that the accelerator proposed by Rabinovich has already been built and put in operation. On the other hand, the scope of utilization of all the known and operating machines is equally unclear. For example, the *Zarnitsa* ionospheric experiment, mentioned above, employed an accelerator that was much weaker than Afonin's elegant and interesting machine listed in Table 2 and designed for the same purpose. While there may have been good technical reasons for using the weaker machine in *Zarnitsa*, it would not be atypical of Soviet practice to forego the stronger model merely because of bureaucratic difficulties or for lack of adequate information.

A better indication of the effort level and current results of Soviet research on the various applications of high-current electron beams may be obtained by analyzing in some detail the theoretical and experimental work of Soviet laboratories and institutions active in this field. Evidence in open-source scientific and technical publications indicates there are a number of researchers at these institutions who are pursuing a broad range of possible applications of high-current electron beams. It is their advances in the direction of possible *technological* applications of these beams that is the focus of this Report.

The Soviet institutions engaged in this work have, for convenience, been divided into two major geographical groupings: the Western and the Siberian.

Table 2  
SOVIET HIGH-CURRENT PULSE ELECTRON ACCELERATORS

Accelerator Designation	Principal Investigator and Laboratory	Operating Parameters			Dielectric	Year	Reference
		E <sub>max</sub> , MeV	I <sub>max</sub> , kA	Pulse Length, nsec			
IMPUL'S	A. A. Kolomenskiy, Lebedev Physics Institute, Moscow	1	30	50	glycerin	1972	2 3
ESU-1 <sup>a</sup>	A. A. Kolomenskiy, Lebedev Physics Institute, Moscow	2	5	35	glycerin	1973	4
-- (b)	M. D. Rayzer, Lebedev Physics Institute, Moscow	0.6	20	20	castor oil	1972	5
proposed <sup>c</sup>	M. S. Rabinovich, Lebedev Physics Institute, Moscow	30	60	100		1972	6
-- (d)	Ya. B. Faynberg, Physicotechnical Institute, Khar'kov	0.4	12	30	water	1970	7
NEPTUN	L. I. Rudakov, Kurchatov Institute of Atomic Energy, Moscow	1	30	40	water	1973	8
TONUS <sup>e</sup>	Tomsk Polytechnic Institute, Tomsk	2	60	50	oil	1973	9
TEREK-2 <sup>f</sup>	B. M. Koval'chuk, Institute of Atmospheric Optics, Tomsk	0.55	10	30	oil	1974	10
RIUS-1 <sup>g</sup>	Ye. A. Abramyan, Institute of Nuclear Physics, Novosibirsk	1	10	100	nitrogen, 16 atm	1972	11
RIUS-5 <sup>h</sup>	Ye. A. Abramyan, Institute of Nuclear Physics, Novosibirsk	4	30	40	SF <sub>6</sub> :N <sub>2</sub>	1971	12
-- (i)	Yu. V. Afonin, Institute of Theoretical and Applied Mechanics Novosibirsk	0.24	4	15	water	1973	13

NOTE: Footnotes to Table 2 appear on p. 7.



The research groups located in Moscow, Khar'kov, and Sukhumi -- the Western groups -- will be discussed here; those in Novosibirsk and Tomsk -- the Siberian groups -- will be the subject of a future Report. The two are roughly equal in size and importance, although they differ to some extent in their research objectives. The Western groups appear to place a greater emphasis on fundamental background research, while those in Siberia may be more active in the design and construction of hardware. However, each contains elements engaged in the development of theory and hardware.

The following are the Western research groups to be discussed in this Report:

1. *The Rudakov Group.* Kurchatov Institute of Atomic Energy, Moscow; research directed by L. I. Rudakov.

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<sup>a</sup>Small size emphasized.

<sup>b</sup>Marx generator is 240 cm long, 90 cm in diameter; includes 22 capacitors in two sections in 4 atm nitrogen,  $C = 5000$  pf,  $L = 2.8$   $\mu$ h,  $\rho = 24$  Ohm. Transmission line is a Blumlein stripline in a cylindrical configuration, 115 cm in diameter, 60 cm high.

<sup>c</sup>Marx generator is 5 m long, 5 m in diameter, coupled to a Blumlein stripline. Diode is of a split type with two dielectrics having a large difference in permittivity (water  $\epsilon = 81$ , oil  $\epsilon = 2$ ) increasing isolation impedance.

<sup>d</sup>Small size. Marx generator is 50 cm long. Pulse-forming line is a Blumlein configuration, 156 mm in diameter (outer cylinder), 500 mm long, 10 nf, 0.5 kJ,  $10^9$  W. Multiple-needle cathode.

<sup>e</sup>Blumlein transmission line is 120 cm in diameter, 5 m long, filled with oil. Multiple-needle cathode.

<sup>f</sup>Pulse autotransformer and Blumlein transmission line, vacuum diode with needle-tip cathode. Accelerator is designed for beam-plasma interaction studies.

<sup>g</sup>Similar to RIUS-5. Coaxial line 100 cm in diameter (internal) and 120 cm long. Needle-cathode. Efficiency of conversion of stored energy to calorimeter-measured beam energy is 20-30%. Designed for beam-plasma interaction studies.

<sup>h</sup>Pulse transformer and coaxial line 1.8 m in diameter and 5.5 m long.

<sup>i</sup>Small size. Tesla transformer and coaxial line, remote light-beam control system, 12-V autonomous power supply. Accelerator designed for installation aboard space vehicles. Efficiency of field-to-electron beam energy conversion is 25%.

2. *The Rukhadze Group*. Laboratory of Plasma Accelerators and Plasma Physics, Lebedev Physics Institute, Moscow; research directed by A. A. Rukhadze.
3. *The Faynberg Group*. Physicotechnical Institute, Khar'kov; research directed by Ya. B. Faynberg.
4. *The Plyutto Group*. Physicotechnical Institute, Sukhumi; research directed by A. A. Plyutto.

The scientists named above have been designated the research leaders not on the basis of official Soviet statements, but rather in view of the apparent key role they play in the context of their published research reports and informal statements in the Soviet press.

The Siberian groups include the one headed by D. D. Ryutov at the Institute of Nuclear Physics in Novosibirsk, the research complex at Tomsk under G. A. Mesyats of the Institute of Atmospheric Optics and the Tomsk Polytechnic Institute, and the V. A. Tsukerman, Ye. A. Abramyan, and G. I. Budker groups. Ryutov has been closely associated with Rudakov in the past and has been concerned with the problem of neutralization of relativistic energy beams, energy transfer from beam to plasma, etc. The main thrust of Ryutov's work is the application of such beams to the heating of plasma in fusion reactors. Some aspects of the work of Mesyats and Tsukerman were treated in previous reports.\* Their group, which specializes in the design of small-size, high-power electron accelerators, has been engaged in a broad range of applications of high-current, high-energy electron beams.

The two groupings do not exhaust the entire Soviet effort dealing with high-current electron beams. For example, recent papers indicate a growing activity at the Yefremov Institute of Electrophysical Equipment in Leningrad to develop high-current electron beams (1 Mev, 20 kA)

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\* Simon Kassel and Charles D. Hendricks, *Soviet Development of Needle-Tip Field-Emission Cathodes for High-Current Electron Beams*, The Rand Corporation, R-1311-ARPA, August 1973; idem, *Soviet Research and Development of High-Power Gap Switches*, The Rand Corporation, R-1333-ARPA, January 1974; Simon Kassel, *Soviet Development of Flash X-Ray Machines*, The Rand Corporation, R-1053-ARPA, October 1973.



in the millisecond pulselength range and to design new inductive storage systems. It is hoped that as such material accumulates, it will be possible to present this work in a subsequent report.

The scope of the present Report is limited to research leading to possible technological applications. Consequently, workers and institutions engaged in high-current electron beam research dealing exclusively with high-energy physics are not covered. Furthermore, less emphasis has been placed on projects employing high-current electron beams exclusively in fusion research. On the other hand, since the Soviet fusion effort has been the mainspring of much of the theoretical and experimental development accomplished by the surveyed institutions, and since it is not possible to separate the fusion aspects of their work, a significant part of the material treated in this Report is pertinent to research on CTR.

An analysis of the research reports issued by the four selected Western groups yielded, in addition to the purely technical material, some insight into the functional relationships among the authors and other members of the Soviet research community active in this and related fields. While all four groups operate in the same broadly-defined subject area of beam-plasma interaction, each has retained its own distinct author membership; personnel interchange among the groups has been negligible during the past ten years of research activity. Considering the fact that the four groups together include over 100 authors, such stability is remarkable by U.S. standards.

Certain authors in addition to the key author stand out within each group. Some play leadership roles by initiating or supervising various lines of research; others review the papers contributed by the group members and act as consultants. These functions are also performed by scientists outside the group, and to this extent, there is some measure of interchange among the four groups.

The participation of leading scientists in the guidance, review, and consultation services rendered to the group authors, and also the intergroup performance of these services, may be taken as a measure of coordination characteristic of this research. For example, B. B. Kadomtsev and R. Z. Sagdeyev, the well-known hot-plasma specialists,

in the millisecond pulselength range and to design new inductive storage systems. It is hoped that as such material accumulates, it will be possible to present this work in a subsequent report.

The scope of the present Report is limited to research leading to possible technological applications. Consequently, workers and institutions engaged in high-current electron beam research dealing exclusively with high-energy physics are not covered. Furthermore, less emphasis has been placed on projects employing high-current electron beams exclusively in fusion research. On the other hand, since the Soviet fusion effort has been the mainspring of much of the theoretical and experimental development accomplished by the surveyed institutions, and since it is not possible to separate the fusion aspects of their work, a significant part of the material treated in this Report is pertinent to research on CTR.

An analysis of the research reports issued by the four selected Western groups yielded, in addition to the purely technical material, some insight into the functional relationships among the authors and other members of the Soviet research community active in this and related fields. While all four groups operate in the same broadly-defined subject area of beam-plasma interaction, each has retained its own distinct author membership; personnel interchange among the groups has been negligible during the past ten years of research activity. Considering the fact that the four groups together include over 100 authors, such stability is remarkable by U.S. standards.

Certain authors in addition to the key author stand out within each group. Some play leadership roles by initiating or supervising various lines of research; others review the papers contributed by the group members and act as consultants. These functions are also performed by scientists outside the group, and to this extent, there is some measure of interchange among the four groups.

The participation of leading scientists in the guidance, review, and consultation services rendered to the group authors, and also the intergroup performance of these services, may be taken as a measure of coordination characteristic of this research. For example, B. B. Kadomtsev and R. Z. Sagdeyev, the well-known hot-plasma specialists,

have been reviewing and consulting for the Faynberg and Plyutto groups in the area of microwave generation and collective acceleration problems. G. I. Budker and V. P. Sarantsev are consultants to the Plyutto group. Intergroup review and consultation is provided by Faynberg for the Rukhadze and Plyutto groups, by Ye. K. Zavoyskiy for the Faynberg and Plyutto groups, and by Rudakov for the Faynberg group.

Each of the following four chapters deals with one of the research groups. To provide an indication of the personnel structure of these groups, each chapter includes a list of personnel, subdivided into the following categories:

1. *Guidance and support.* This designation includes the group leader and, in most cases, other members who have been acknowledged as initiators or supervisors of research.
2. *Review.* This category designates a specific function of reviewing (evaluating) research papers.
3. *Consultation.* This category consists of consultants outside the group membership and applied only to the Rukhadze and Plyutto groups.
4. *Senior authors.* This category includes all authors in the group who participate in guidance, review, and consultation activities.

## II. THE RUDAKOV GROUP

### A. INTRODUCTION

Unlike the other major Soviet researchers of high-current electron beams, Rudakov does not indicate an institutional affiliation in his publication by-line. Rather, his institutional association is indicated in the open-source literature only indirectly, by statements of others, or by the affiliation of his coauthors. His association with Academician Ye. K. Zavoyskiy places him at the Kurchatov Institute of Atomic Energy in Moscow, at least in the early years, and several of his coauthors were identified with the Kurchatov Institute in papers published in 1972 and 1973. At the same time, Rudakov is associated with the fusion research group of D. D. Ryutov at the Institute of Nuclear Physics, Siberian Department, USSR Academy of Sciences, in Novosibirsk.

The leadership of the Rudakov research group is as follows:

#### *Guidance and Support*

Ye. K. Zavoyskiy  
L. I. Rudakov  
K. I. Tarakanov

#### *Review*

Ye. K. Zavoyskiy  
L. I. Rudakov  
A. A. Ivanov

#### *Senior Authors*

Ye. K. Zavoyskiy  
L. I. Rudakov  
A. A. Ivanov  
S. L. Nedoseyev  
I. V. Novobrantsev  
A. A. Vedenov (up to 1966)  
L. V. Korablev (up to 1966)

#### *Experimentalist-Authors*

S. S. Kingsep  
G. P. Maksimov

It is clear that Academician Zavoyskiy has been participating directly in the group's research work, and he has been acknowledged regularly for his assistance and interest. He appeared as a coauthor

a few times, but only in the early years of the work. In terms of frequency of publications, acknowledgments, and coauthorship, Rudakov is obviously the group leader on the working level.

Rudakov's plasma work dates back to the fifties, when he participated with Zavoyskiy in developing methods of turbulent heating of plasma for fusion reactors at the Kurchatov Institute. He, Zavoyskiy, and R. Z. Sagdeyev, were the central figures in the research activities that led to the formulation of the theory of collective motion of charged particles in plasma, two-stream instability, and anomalous resistance of plasma, a theory that could be applied to effective plasma containment and production of plasmas with thermonuclear parameters.

Throughout the intervening years Rudakov remained closely associated with controlled thermonuclear reaction research, first studying direct-current heating of plasma, and later taking up the application of electron beams to heat plasma in various types of fusion reactors and the stability of high-current electron beams injected into dense plasma. It is noted that most of Rudakov's papers, unlike those of the other major Soviet researchers in this field, show no interest in inertial heating. A single exception is a paper, presented at the Sixth International Fusion Conference in Moscow [14], in which he considered a DT gas mixture in a high-Z shell heated by an electron beam via implosion of the shell.

Rudakov's recent work has been devoted to the study of the behavior of electron beams in dense plasma to solve the problems of *passing relativistic beams through plasma* and of creating plasmas with thermonuclear parameters [15]. Both problems require the investigation of beam stability, although the first calls for the suppression of all instabilities, while the second depends on the enhancement of some types of instability. Rudakov considers the excitation of Langmuir waves in plasma to be the principal mechanism of beam-plasma interaction. The nature of this mechanism depends on the relative densities of the charged particles in the beam,  $n_b$ , and in the plasma,  $n_p$ ; the average velocity,  $v$ , of the beam; the initial

angular velocity dispersion (in the momentum space),  $\phi = \Delta p / p$ , of the beam; the frequency of Langmuir oscillations,  $\omega_L$ , in plasma, and other factors.

Two basic instability modes are the hydrodynamic mode and the kinetic mode. In the hydrodynamic mode, a beam that is nearly monochromatic, having a small initial thermal velocity dispersion  $\Delta v$ , may undergo a rapid dissipation in the plasma. The process is amenable to a quasilinear analytical treatment. In the kinetic mode, if beam has high energy and the initial  $\Delta v$  is large, dissipation of the beam can occur only via induced Cherenkov effect and represents a nonlinear process.

In the course of beam-plasma interaction, the initial hydrodynamic mode may give way to the kinetic mode as a result of a consequent increase of  $\Delta v$ . In general, the length of the beam dissipation path is longest in the kinetic mode, and under some conditions the beam may pass through plasma without a significant loss of energy [16].

#### B. QUASI-LINEAR THEORY

The linear approximation of beam instability due to the collective dissipation mechanism fails to produce satisfactory results. The quasi-linear approximation, which takes into account the feedback effect of instability oscillations on the beam, is acceptable if the beam is sufficiently monochromatic and its energy is moderate.

The hydrodynamic instability mode is possible only if the thermal  $\Delta v$  of the beam is below a threshold value defined [15] as

$$\frac{\Delta v}{v} < \frac{\delta_0}{\omega_L}$$

where  $\delta_0 = \omega_L (n_b / n_p)^{1/3}$  is the maximum beam instability growth rate for  $n_p \gg n_b$ . The instability growth rate  $\delta$  for relativistic beams strongly depends on the angle  $\theta$  between the direction of the oscillation wave vector  $k$ , and  $v$ . The dynamic decrease of  $\delta$  from the initial value typical of a monochromatic beam is the result of an increasing



angular velocity dispersion  $\phi$  and of the transition to the kinetic mode of instability [16].

If the electron beam is nonrelativistic, an initially monochromatic beam excites oscillations with a practically constant  $\delta$  within a large  $\theta$ . The instability is kinetic and can be described by quasi-linear equations. However, for certain values of  $\phi$ , i.e.,  $(n_b/n_p)^{1/3} < \phi < \frac{1}{\gamma}$ , the beam rapidly becomes dissipated because of developing hydrodynamic instability.

If the beam is strongly relativistic, the initial stage of propagation, where  $\phi$  increases, continues until  $\phi = \gamma^{1/2}(n_b/n_p)^{1/6}$ . This value of  $\phi$  is sufficient to disrupt monochromaticity for all  $\theta$ , in contrast to the case of a nonrelativistic beam. Hydrodynamic instability is not significant in such a case.

However, of the greatest practical interest is the case of an initially nonmonochromatic beam injected into plasma, where the velocity dispersion is due to beam focusing. If  $\phi > \gamma^{1/2}(n_b/n_p)^{1/6}$ , only the kinetic instability mode is possible. The interaction produces mostly oscillations with small  $\theta$ ; these determine the diffusion coefficient and tend to dissipate the beam without further increasing  $\phi$ .

The dissipation time of a velocity-dispersed beam is determined by the initial  $\phi$ :

$$t\omega_L \approx \frac{n_p \gamma}{n_b} \phi^2; \quad \phi > \frac{1}{\gamma}$$

This is considered an important result of the quasi-linear theory [16].

### C. NONLINEAR THEORY

Scattering of Langmuir oscillations induced by plasma particles can limit the oscillation level and increase the dissipation path length; it may even completely suppress the instability. Rudakov determines its effect on the dissipation of a strong electron beam in a dense plasma [16] as follows.

Nonlinear scattering of Langmuir oscillations induced by plasma particles shifts the oscillations toward higher phase velocities. Although no resonance interaction with particles is possible when  $\omega/k > c$ , the accumulation of energy in this phase velocity range affects the growth rate of unstable oscillations in the range  $\omega/k < c$ . Hence the nonlinear effect. The nonlinear scattering by plasma electrons can almost completely suppress instability if the energy density stored in the  $\omega/k > c$  region is high. After this level has been reached, the residual instability may be due to the damping effect of Coulomb collisions.

The general theory is applied to the specific case of a dense plasma with a high frequency of Coulomb collisions and strong radial inhomogeneity caused by heat from the self-focusing of the beam. The plasma is in thermal equilibrium ( $T_i = T_e > 0.5$  keV). The principal effects under these conditions are that the transfer of oscillations from the unstable region of phase velocities occurs only via scattering by electrons. Scattering by ions merely reduces the noise energy in the unstable region.

The region of strong kinetic instability where oscillations mainly occur is narrow in terms of phase velocities  $\Delta(\omega/kc) \approx 1/2\phi^2$  and of the solid angle  $\theta < \phi$ .

The region of  $\omega/k > c$  is the nonresonance region. Nonlinear scattering does not change the nature of  $\delta(\phi)$ . Consequently, as in the quasi-linear theory, beam instability primarily dissipates the beam by axial momentum dispersion. The angular dispersion  $\psi$  remains small and practically does not change during dissipation.

In the case of a monochromatic beam, nonlinear effects increase, rather than suppress, the ("explosive") instability, since unstable oscillations have a negative energy.

#### D. OTHER MECHANISMS OF COLLECTIVE DECELERATION

Beam focusing by self-magnetic field and plasma heating by dissipation of counterstreaming current were considered in [17]. From the viewpoint of plasma heating, it is important to consider that the electrical conductivity,  $\sigma$ , of plasma rapidly increases with temperature.



On the other hand, plasma turbulence caused by an unstable beam significantly decreases  $\sigma$ . Turbulent heating can be caused by ion-acoustic instability, possible when  $T_e > T_i$ , which in turn, is obtained when the counterstreaming current density exceeds the beam current density.

From the viewpoint of beam transport through plasma, the most dangerous instability is that causing a transverse shift of the entire beam, i.e., the hose instability. However, the flow of relativistic electrons can follow only a magnetic channel. Often a new magnetic channel can be established by the beam only in a time interval that is longer than the interval since injection. Therefore, such an instability is not dangerous for fast processes. To avoid hose instability, the beam radius must be larger than the product of the velocity of sound in plasma and the time since injection [17]. Another mechanism of instability not covered by the theory of frequency shift due to induced Langmuir oscillations is a turbulence state characterized by the presence of solitons [18]. The nonlinear theory of spectral shift breaks down when

$$\omega/(nT) > \overline{\Delta k^2} r_D^2$$

where  $\overline{\Delta k}$  is the spectral width,  $r_D = v_{Te}/\omega_L$ , and  $v_{Te} = 2T_e/m$ .

The turbulence can be maintained by beam instability when the oscillations excited in plasma by the beam satisfy the above inequality, leading to the bunching of the Langmuir oscillation energy. As a result, there arise in plasma bound states that are qualitatively different from traveling waves and are localized in space. These Langmuir oscillations are called solitons. They represent sets of plane waves with matched phases and amplitudes.

In a strongly turbulent plasma, one can excite electric fields up to GV/cm, capable of effectively thermalizing any ordered motion such as that of an electron beam.

#### E. EXPERIMENTAL DATA

Materials on Rudakov's experimental research involving high-current electron beams have been published since 1972. The accelerator used in these experiments is the *Neptun*, apparently designed by Rudakov's group.

The Neptun accelerator [see Fig. 1] delivers 10- to 30-kA, 0.5- to 1-MeV, 40-nsec pulses. Its special feature is a Blumlein stripline filled with distilled and degassed water serving as the dielectric, claimed to have made it possible to reduce the size of the machine significantly and to simplify fabrication and maintenance [8]. The use of water in this design is based on the work of Tsukerman and Pecherskiy [19].

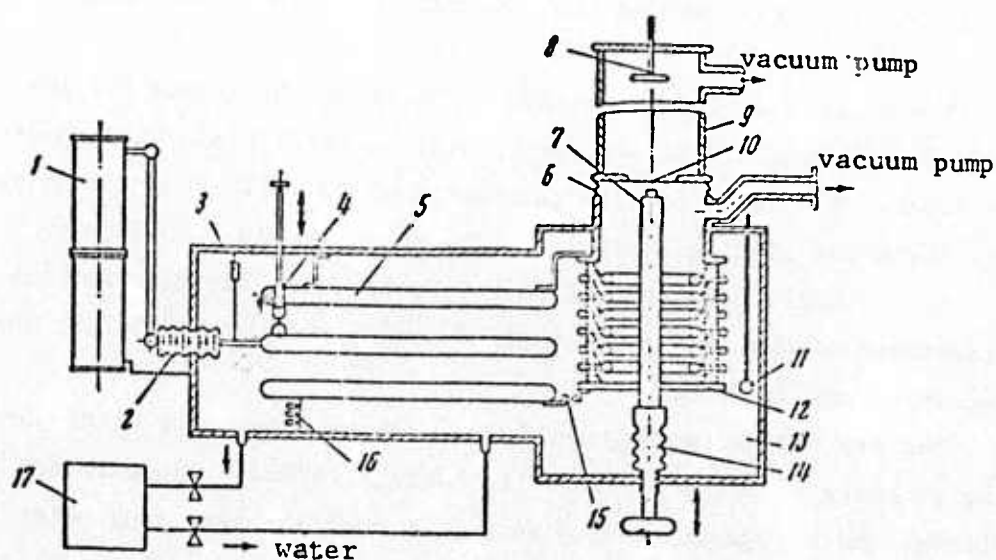


Fig. 1 -- Neptun accelerator [8]

- 1 - GIN-400-0.06/5 voltage generators
- 2 - high-voltage input
- 3 - meter resistor
- 4 - gap switch
- 5 - stripline
- 6 - shunt
- 7 - cathode support
- 8 - calorimeter
- 9 - drift chamber
- 10 - anode foil
- 11 - capacitive pickup
- 12 - diode
- 13 - chamber
- 14 - insulator
- 15 - pulse-shaping gap
- 16 - inductance
- 17 - water purifier

The accelerator is housed in a stainless steel tank filled with water. The tank can withstand 5 atm. The Blumlein stripline is 65 cm long, with 50-mm spacing between strips. The central strip is charged to 1.1 MV.

The diode consists of seven Plexiglas rings 200 mm in diameter and 20 mm thick, separated by anodized aluminum gradient rings and sealed with vacuum rubber. Vacuum is  $3 \times 10^{-5}$  to  $10^{-4}$  torr. Aluminum or titanium anode foil is 50  $\mu\text{m}$ . Measurements of potential along the diode axis showed that maximum deviation from linearity did not exceed 40 percent.

The cathode is movable without disrupting the vacuum for impedance matching. It is a 0.1-mm stainless steel plate with about 200 holes. The inner side of cathode is filled with epoxy resin to facilitate the sliding discharge. The diode gap is 5 to 10 mm.

Two standard GIN-400-0.06/5 generators in series have a total capacitance of  $6 \times 10^{-9}$  f and maximum energy charge of 1.5 kJ. The load impedance is 30  $\Omega$ .

The gap switch is actuated by water breakdown. The water purifier consists of a TsNG-70 pump, mechanical filters, ion-exchange resin columns, and a degassing vaporizer. The purifier can bring water resistivity to 6 Mohm.cm in 1.5 to 2 hours and restore its dielectric properties after prolonged operation. Preliminary tests showed that the electrical strength of purified and degassed water exceeds 40 kV/mm for voltage pulses of 0.2  $\mu\text{sec}$ . The electrical strength of the gap after discharge is fully restored. This allows the use of the old water-breakdown gaps developed by Mesyats in 1962.

In the operation of the accelerator, the minimum pulse rise time was 5 to 7 nsec for 10- to 15- $\Omega$  lines at 1.0 to 1.5 MV/cm. The average pulse front was 15 nsec. The gap switch was adjusted for a breakdown of 0.8 to 0.9  $V_{\text{max}}$  (charging voltage).

The maximum gap switch voltage was 1 MeV, and maximum beam current was 30 kA. Up to 30 percent of stored energy went into the beam. Maximum beam current density was 3 kA/cm<sup>2</sup>. For beam current of  $\sim 20$  kA, the cathode sustained 2000 pulses. At 700 kJ and 20 kA, the tube withstood  $> 1000$  pulses. In operation at maximum parameters, the diode

deteriorated faster because of vacuum breakdown along the insulator surface [8].

A series of experiments were performed with the Neptun accelerator to determine the ionization mechanism [20] and the path length of the electron beam in the drift tube at near-atmospheric pressures [21].

Two possible ionization mechanisms were considered: ionization by secondary electrons due to the self-field of the beam and ionization by fast electrons of the beam. In the ionization study experiment (Fig. 2), a 0.66-MeV, 10- to 20-kA beam was admitted through a 100- $\mu$ m foil into the drift tube. The diameter of the beam at the entrance to the tube was 4 to 5 cm [20].

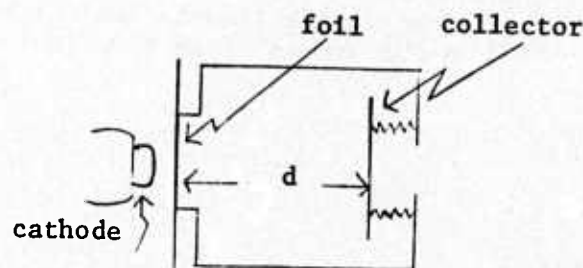


Fig. 2 -- Experimental setup to determine ionization mechanism and e-beam path length with Neptun accelerator [20]

The oscilloscopic traces in Fig. 3 were obtained by a shunt on the perimeter of the anode flange with a time resolution of  $\leq 2$  nsec. The correspondence between the shunt readings and the true beam current was secured with a Faraday cup located directly behind the foil, with the neutral gas pressure in the drift tube not over  $5 \times 10^{-2}$  torr. Up to  $10^{-2}$  torr, the ionization time by relativistic electrons is larger than beam injection time  $\tau$ , and plasma density is insufficient for neutralization. For  $p > 0.1$  torr, charge neutralization occurs, but density is still insufficient for magnetic neutralization. Further increase of pressure causes a sharp increase of ionization by secondary electrons, generating a counterstreaming current. Total

current amplitude as a function of pressure is shown in Fig. 4 for a drift tube with  $d = 80$  cm. As pressure rose above 300 torr,

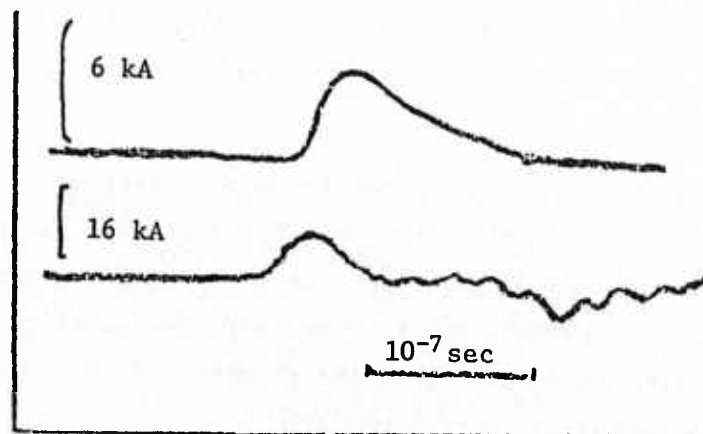


Fig. 3 -- Oscilloscopic traces of total current (upper line) and beam current (lower line) in helium at 0.1 atm as functions of time [20]

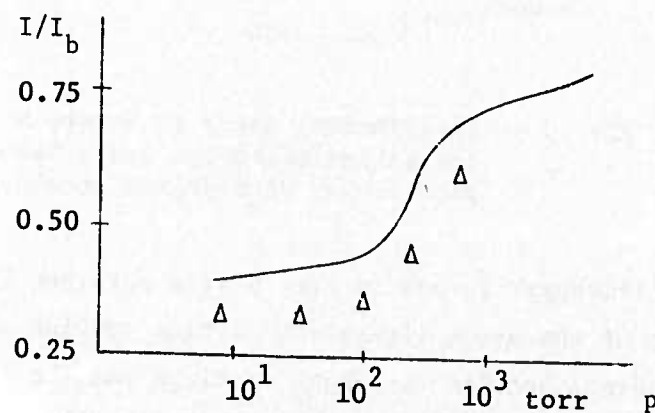


Fig. 4 -- Ratio of total current and beam current peaks as a function of pressure [20]

$I$  - peak total current to collector

$I_b$  - peak beam current

$\Delta$  - experimental points

beam path length decreased to 10 to 20 cm. The principal experiments comparing theoretical calculations with experimental data were performed at  $d = 20$  cm and collector diameter of 17 cm.

The gases used in the experiment were helium and nitrogen, the latter to approximate air. It was found that secondary-electron ionization predominates below 1.5 atm for helium and below 0.3 atm for nitrogen.

The path-length experiments were performed under similar conditions, except that air was used instead of nitrogen (Fig. 5).

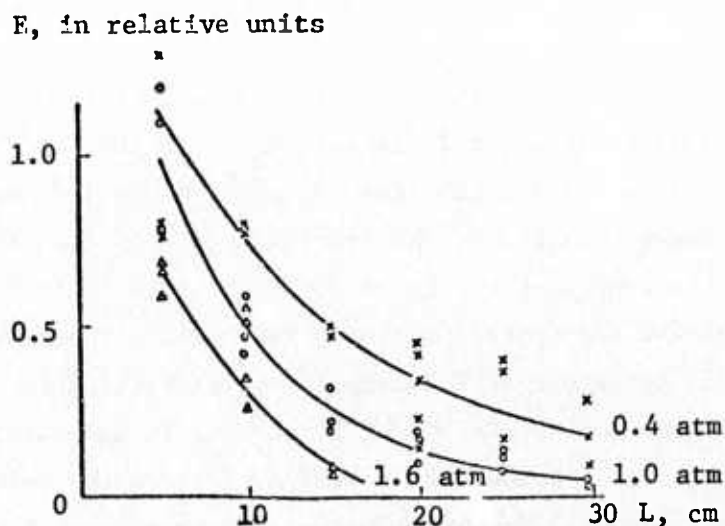


Fig. 5 -- Distribution of beam energy falling on a calorimeter along the drift tube axis, for air [21]

At 1 atm in air, the beam path  $L$  was 12 cm in a drift tube 80 cm long and 18 cm in diameter. The path shortened from 20 to 10 cm as pressure rose from 0.4 to 1.6 atm. In helium, the path was found to be longer than the drift tube for all gas pressures up to 1.6 atm. Beam attenuation is attributed to instability in a dissipative medium. The electron scattering frequency in a relatively dense plasma ( $10^{14}$  to  $10^{16}$   $\text{cm}^{-3}$ ) is high ( $4 \times 10^{12}$   $\text{sec}^{-1}$ ).

The behavior of small beam density perturbations is expressed by a dispersion equation with an unstable solution causing beam bunching.



The perturbation increases faster than its attenuation rate caused by velocity dispersion. Bunching decelerates the beam through dissipation of the counterstreaming current induced in plasma. In addition, beam dissipation may also be due to the leakage of beam particles to the walls due to increased radial velocities induced by the electric field. On the basis of these considerations, Rudakov specifies theoretical limits for the beam path length  $L$  [21]:

$$\gamma \frac{n_p}{n_b} \frac{\overline{\Delta v}}{v} < L < \gamma \frac{n_p}{n_b} \frac{v}{v}$$

where  $v$  is the electron scattering frequency, and  $\overline{\Delta v}$  is the thermal velocity dispersion.

He then attempts to evaluate  $L$ , using some of the following experimental parameters: For 1 atm air,  $n_b = 2 \times 10^{11} \text{ cm}^{-3}$ ,  $n_p = 2 \times 10^{15} \text{ cm}^{-3}$ ,  $v = 4 \times 10^{12} \text{ sec}^{-1}$ , and  $\Delta v = 5 \times 10^9 \text{ cm/sec}$ . Substituting these values into the left-hand side of the above inequality and assuming that  $\gamma = 2$ , we obtain a lower limit for  $L$  of 25 cm. Similarly, the upper limit of  $L$  is 130 cm. These values appear to be in agreement with Rudakov's experimental data. Rudakov notes that his theoretical values of  $L$  are also in agreement with the experimental results obtained by W. T. Link [22] in the United States. Link's results, measured for atmospheric air, were about 4 times longer than the Soviet results, a difference that Rudakov attributed to the higher beam energies used in the U.S. experiments.

Rudakov's theory was criticized by V. K. Grishin and V. G. Sukharevskiy of the Lebedev Physics Institute [23], who noted that his dispersion equation was nonrelativistic and limited to electrostatic oscillations only. In their approach, based on the dispersion equation of electromagnetic oscillations, they arrive at a lower limit of  $L$

$$L \geq \gamma^3 \frac{n_p}{n_b} \frac{\Delta v}{v}$$

which is  $\gamma^2$  times longer than Rudakov's limit for electrostatic oscillations.

Another series of experiments with the Neptun accelerator was aimed at determining the effect of filling the vacuum diode with plasma from an external source. The plasma source was designed as part of the diode structure (Fig. 6).

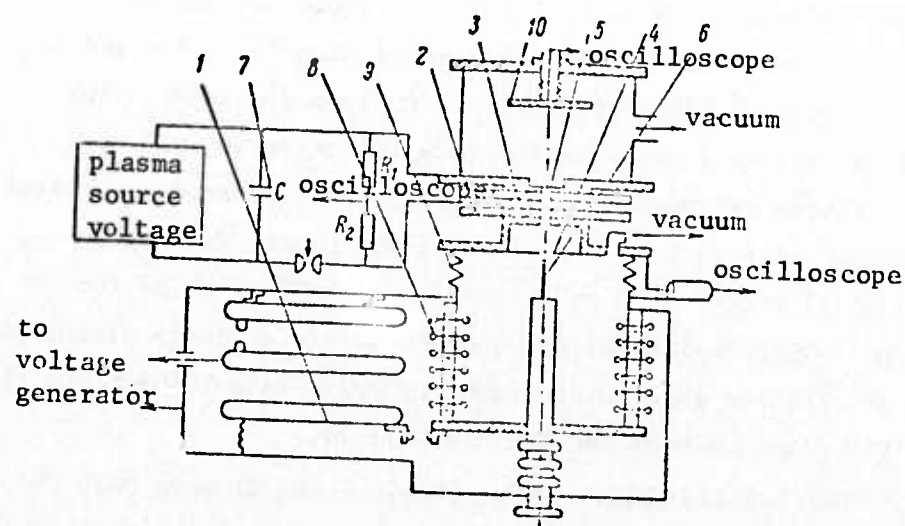


Fig. 6 -- Neptun accelerator with plasma-filled diode [24]

- 1 - Blumlein transmission line
- 2 - organic glass discs
- 3 - plasma-source metal electrodes
- 4 - anode disc with hole
- 5 - tantalum foil
- 6 - diode cathode
- 7 - plasma-source capacitor bank
- 8 - diode insulator
- 9 - meter shunt
- 10 - Faraday cup

Operating in the vacuum mode, the diode had the following parameters: cathode diameter, 40 mm; anode foil, 50  $\mu$ m thick; optimum match gap width, 8 mm; beam voltage, 0.7 MV; beam current, 17 kA; beam pulse length, 50 nsec; current density at anode,  $1.3 \times 10^3$  A/cm<sup>2</sup>.

In plasma-filled operation, plasma was derived from a discharge on the surface of a cylindrical channel drilled through two Plexiglas discs separated by metal electrodes; the discs were 6 mm thick; the



channel was 20 mm long and 5 mm in diameter; a 0.05- $\mu$ f, 30-kV capacitor was discharged through the central electrode, with the other two electrodes grounded; a plasma jet emerged from the channel into an expansion chamber and was collimated by a 5-mm hole in the anode. The opposite end of the plasma source channel was covered by titanium foil 50  $\mu$ m thick. A Faraday cup was placed beyond the foil to measure electron beams above 1 kA. The diode cathode was a stainless steel cylinder 30 mm long and 5 mm in diameter. The end face of the cathode was in most experiments 8 mm from the anode. The diode gap and the plasma source channel were evacuated to  $10^{-5}$  torr.

Plasma parameters were measured in a separate experiment. At a distance of 8 mm from the anode plane, plasma density in the channel reached  $2 \times 10^{12}$   $\text{cm}^{-3}$  in 10  $\mu$ sec, with half-width of the jet of 10 to 12 mm. Reproducibility was good enough to evaluate plasma parameters in accelerator experiments from the delay time between the operation of the plasma source and the accelerator.

The oscilloscopic traces (Figs. 7 and 8) show that the diode current strongly depends on plasma density. Matching is obtained for  $n_p \approx (2-3) \times 10^{12}$   $\text{cm}^{-3}$  where total diode current  $I_{\text{max}} = 20$  kA and beam diameter is 10 to 12 mm. The corresponding current density is 20 kA/ $\text{cm}^2$ . This is 10 to 15 times  $I_{\text{max}}$  of the vacuum diode. Electron beam density is  $(3-4) \times 10^{12}$   $\text{cm}^{-3}$  which is close to ion density in the diode gap.

In the experiments, the Blumlein transmission line was matched to the diode when gap ion density was lower than beam electron density by a factor of 2 to 3. In this case the beam is only partially neutralized by the ions. If  $n_e = n_i$ , any beam densities can be theoretically obtained without shortening the gap. In practice, however, beam density is limited by the voltage source, beam inductance, and the possible instabilities of the neutralized beam. In this case the critical current is  $I_{\text{cr}} = (m_e/e)(a^2/L^2)c^3$  (where  $a$  and  $L$  are diameter and length of beam respectively). In these experiments,  $I \ll I_{\text{cr}}$ .

For a completely charge-neutralized beam, electron acceleration can be limited by anomalous resistance of plasma due to ion-acoustic

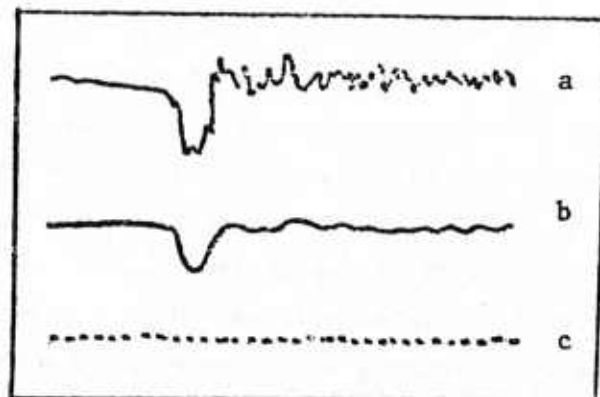


Fig. 7 -- Oscilloscopic traces of vacuum diode operation [24]

- a - voltage
- b - current
- c - timing marks = 20 nsec

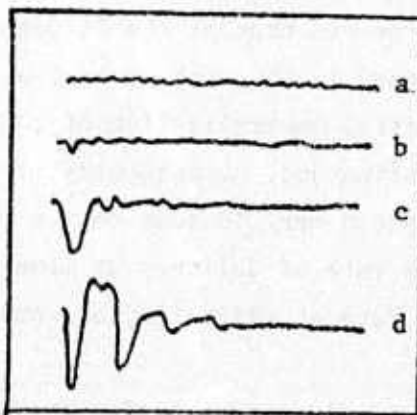


Fig. 8 -- Oscilloscopic traces of plasma-filled diode operation, sweep = 1  $\mu$ sec [24]

- a - plasma density  $n_p = 0$
- b -  $n = 0.8 \times 10^{12} \text{ cm}^{-3}$
- c -  $2 \times 10^{12} \text{ cm}^{-3}$ , 20 kA
- d -  $n_p = 10^{13} \text{ cm}^{-3}$

or Buneman instability [25]. This can readily occur in these experiments:  $E \gg E_{Dr} = 10^{-12}(n/T_e)$  V/cm ( $E_{Dr}$  is the Dreiser field limit) and  $j \gg j_{cr} = en\sqrt{T_e/m_e}$ . The anomalous resistance of the diode could thus be attributed to the scattering of electrons by the turbulent pulsation of plasma. The effective frequency of such scattering is  $\nu_{eff} \sim 10^{10}$  sec<sup>-1</sup>. However, such a scattering would convert part of the electron energy into heat, decreasing the beam energy well below the applied voltage. This was not observed in the actual experiments. Assuming that the heated electrons are undergoing turbulent diffusion across the self-magnetic field, the measured diameter of the current column yields the maximum value of the thermal electron velocity  $v_{Te} < 2 \times 10^9$  cm/sec. Consequently, the thermal conductivity of turbulent plasma,  $\chi \approx v_{Te}^2 / \nu_{eff} \leq 10^9$  cm<sup>2</sup>/sec, is very low, and the energy,  $W = I^2 R t \simeq 500$  J, transmitted from the line to the gap is not dissipated as heat, but carried away by the electron beam having the parameters of  $v_e \sim 0.7$  MeV and  $I \simeq 20$  kA.

It is noted that collective effects can be used to generate electron beams within the plasma diode by the application of electric fields  $E > E_{Dr}$ , as reported by Plyutto and Suladze [26]. In Rudakov's experiment, in contrast to that of the Plyutto group, the relativistic electron beam is formed in the cathode region, and the plasma ions merely provide a partial neutralization of the beam charge. The degree of neutralization and, consequently, the distribution of potential in the gap can vary in time due to the variation of ion density, because the rate of delivery of ions to the gap does not generally equal the rate at which they are pulled off by the electric field.

The plasma-filled diode gap, beside increasing beam density, also simplifies the problem of transporting and injecting high-current electron beam in various experimental devices.

### III. THE RUKHADZE GROUP

#### A. INTRODUCTION

The research team headed by A. A. Rukhadze is distinguished among the groups discussed in this paper by the broadest range of interests and applications involving high-current electron beams. This range is reflected in the personal orientation of Rukhadze himself, who frequently writes survey and popular articles on the developments and research aims in this subject area.

Rukhadze, who holds the academic degree of Doctor of Physico-mathematical Sciences, is designated in Soviet publications as a theoretical physicist specializing in the physics of plasma and electrodynamics of matter. He works under M. S. Rabinovich at the Laboratory of Plasma Accelerators and Plasma Physics of the Lebedev Physics Institute in Moscow. The theoretical work of his group is associated to an appreciable extent with fusion research and, like that of many other groups in this area, probably originated from the early phases of controlled fusion theory. Its main thrust at this time, however, is the establishment of detailed stability criteria for the beams and plasma that can be applied to the solution of many practical problems. Theoretical analysis of high-current beams involves a comprehensive evaluation of magnetic and electrostatic neutralization conditions determining the limiting and critical currents. The principal application outside fusion is the production of new types of powerful microwave oscillators. To this end, Rukhadze's group pursues research in several parallel directions, investigating electron beam interaction with gaseous plasma, solid-state plasma, and periodic spatial structures in vacuum. There is also an interest in the application of such beams to ionospheric sounding and the behavior of beams in the atmosphere. Finally, Rukhadze is active in the development of exploding wire techniques as a means of laser pumping.

The following is the leadership of Rukhadze's group:

*Guidance and Support*

A. A. Rukhadze

V. P. Silin

*Review*

A. A. Rukhadze

V. P. Silin

M. S. Rabinovich

Ya. B. Faynberg

G. M. Batanov

L. M. Kovrizhnykh

V. P. Brodskiy

Yu. N. Dnestrovskiy

D. P. Kostomarov

G. P. Mkheidze

*Consultation*

M. V. Nezlin

V. M. Levin

G. V. Mikhaylov

V. B. Rozanov

A. A. Samarskiy

S. P. Kudryumov

L. M. Degtyarev

A. P. Favorskiy

*Senior Authors*

A. A. Rukhadze

V. P. Silin

L. M. Kovrizhnykh

Ye. Ye. Lovetskiy

S. Ye. Rosinskiy

G. P. Mkheidze

B. PLASMA INSTABILITIES

Research in this area, carried on mainly by V. P. Silin, with occasional help from L. M. Kovrizhnykh and Ye. Ye. Lovetskiy, has been in progress since the late fifties and exclusively theoretical. It focuses on the stability of spatially inhomogeneous plasma confined by a strong magnetic field, considered from the viewpoint primarily of controlled thermonuclear reaction research, and secondarily, of possible benefit to the study of ionospheric and interplanetary plasmas and gaseous discharge [27].

Silin's approach is based on the use of the geometric optics approximation in the solution of plasma instability problems [28], thus eliminating the spurious spatial dependence of plasma oscillation spectra obtained by other authors, including L. I. Rudakov. In his earlier papers [29, 30], Silin performed a one-dimensional analysis, applying dispersion equations similar to the quasi-classical Bohr quantization laws. This was later [31] extended to three-dimensional instability models involving high-frequency longitudinal and transverse electron oscillations, low-frequency nonacoustic oscillations, and low-frequency oscillation of cold magneto-active plasma. Similarly, from the analysis of collisionless dissipation processes due to the absorption and emission of waves in plasma [29, 32, 33, 34], Silin progressed to consider the effect of charged-particle collisions on the drift instability [35]. This had been investigated by others using the Batnagar-Gross-Krook collision integral; Silin showed that the BGK integral was not applicable to plasmas with temperature inhomogeneity and that the correct results could be obtained only with the Landau collision integral.

In the study of the role of charged-particle collisions in plasma stability, Silin considers only the kinetic theory and disregards the hydrodynamic view of plasma. He thus focuses on the drift-dissipative instability of completely ionized plasma, taking Coulomb collision and transverse interactions into account. The significance of the collision effects is based on the fact that in thermonuclear plasma with  $N \sim 10^{14}$  to  $10^{15} \text{ cm}^{-3}$ ,  $T \sim 1$  to  $10 \text{ keV}$ ,  $L_0 \sim 10 \text{ cm}$  (characteristic dimension of inhomogeneity), and  $B_0 \sim 10^4$  to  $10^5 \text{ Oe}$ , the most dangerous fundamental modes of drift oscillations  $\omega_{dr}$  are  $\nu_e \sim 10^4$  to  $10^5 \text{ sec}^{-1} \gtrsim \omega_{dr} \sim 10^3$  to  $10^4 \text{ sec}^{-1} \gtrsim \nu_i \sim 10^2$  to  $10^{-3} \text{ sec}^{-1}$ , where  $\nu_e$  and  $\nu_i$  are the effective collision frequencies of electrons and ions.

### C. CRITICAL AND LIMITING CURRENTS IN E-BEAMS

This group working under Rukhadze consists of L. S. Bogdankevich, V. P. Tarakanov, I. I. Zhelyazkov, M. D. Rayzer, P. S. Strelkov, S. Ye. Rosinskiy, V. G. Rukhlín, and Ya. G. Epel'baum. For a number of years, from the late sixties to 1972, it has been concerned directly with



determining the theoretical stability criteria and limits of current in electron beams. The investigation of these problems stemmed from the attempt to obtain the maximum possible current in the beam. The physical configuration studied in these efforts was an electron beam inside a metal waveguide collimated by a strong axial magnetic field.

The long-range aims of this research, explicitly stated by various members of the group [36, 37], were concentrated in the following areas:

- o High-power electronics.
- o Intense sources of X-rays and microwaves.
- o Accelerator technology.
- o Controlled fusion reactions.
- o Long-distance energy transmission.

Initially, the group attempted to provide a systematic classification of all instabilities of neutralized electron beams and to determine the current limitations due to these instabilities. The theoretical foundation of this attempt was derived from Silin's work on the stability of spatially inhomogeneous plasma in the geometric optics approximation (see Section III, B). According to Silin's theory, the criticality of the beam current is governed by the effects of short-wave instabilities; however, this is not the case in actual electron beams. The current in electron beams is limited by longwave instabilities whose wavelength exceeds the beam diameter (see, for example, the criterion of Section II, D).

The researchers then went back to the early postulates of Pierce, Smith, and Hartman for determining the theoretical values of the limiting current (defined as the maximum possible current in the electron beam) and the critical current (defined as the minimum current that gives rise to instabilities). From that point on, they began to develop successive values for the critical current corresponding to different types of instability arising with increasing beam current and energy.

For a relativistic electron beam in vacuum, the theoretical interpolation formula for the limiting current in stationary operation is [36]

$$I_{lim} = \frac{mc^3}{e} \frac{(\gamma^{2/3}-1)^{3/2}}{1 + 2 \ln R/r}$$

where  $R$  and  $r$  are the drift tube and beam radii, respectively, and it is assumed that  $R \gg r$ . Recently, this formula was tested experimentally [38] and found to be reasonably valid. Specifically, the test involved a 600-keV, 7.5-kA, 20-nsec electron beam in a drift tube 3 cm in diameter and 100 cm long. The results of the measurements are given in Table 3. Here  $I_1$  is the current measured directly behind the diode,  $I_{lim}$  is the current computed from the theoretical formula,  $I_z$  is beam current at the collector at the end of the drift tube, and  $E$  is the electron beam energy. Several values of the  $R/r$  ratio were used.

Table 3 [38]

COMPARISON OF EXPERIMENTAL  $I_1$  AND  $I_z$  AND  
THEORETICAL  $I_{lim}$  FOR A DRIFTING BEAM IN VACUUM

$R/r$	$I_1$ , kA	$I_{lim}$ , kA	$I_z$ , kA	$E$ , J
2.4	7.5	4.0	4.5	53
3	5.0	3.2	3.6	42
4	2.8	2.6	2.0	22
6	1.0	2.2	1.0	9.5

The vacuum in the drift tube was  $10^{-5}$  mm Hg. An external magnetic field was varied from 2000 to 8000 Oe. Both currents,  $I_1$  and  $I_z$ , and current density distribution over the beam cross-section remained unaffected by the increase of  $B$  to 8000 Oe. Since  $I_1$  was in most cases larger than  $I_{lim}$ , the measured values of  $I_z$  are considered the maximum current permitted by the drift tube. Since the pulse front was  $\leq 10$  nsec and the time of flight of the beam electrons was 3.3 nsec, the experiment was considered sufficiently close to the approximation of stationary operation.

Nonstationary phenomena, however, must be taken into account in the generation of pulsed beams of  $10^5$  to  $10^7$  A. It was shown [39]



that in the process of pulse formation, part of the kinetic energy of the electrons is spent on the establishment of the magnetic self-field. This limits the maximum beam currents by about 10 percent and modifies the energy spectrum of the electrons.

Assuming a nonrelativistic neutralized homogeneous e-beam, the critical current is given by the Pierce formula

$$I_{cr} = \frac{mv^3}{4e} \frac{(2.4)^2}{1 + \ln R/r}$$

where  $R$  and  $r$  are the waveguide and beam radii, respectively. This limit is imposed by the Buneman hydrodynamic instability [40]. However, experiments showed that neutralized beams in axial magnetic field may become unstable below  $I_{cr}$  due to the current-convective instability, which then becomes the limiting factor, unless stabilized by a very strong magnetic field  $\gtrsim 50$  kOe, which is difficult to obtain experimentally.

The current-convective instability decreases the critical current to

$$I'_{cr} = \frac{I_{cr}}{1 + \eta}$$

where  $\eta \approx Lv/r^2\Omega$  ( $L$  is the beam path length in plasma and  $r$  is beam radius).

After beam neutralization has taken place, the ionization of residual gas produces dense secondary plasma, which further limits the current below  $I'_{cr}$  due to two-stream and electron current-convective instabilities. Rukhadze [40] proposes the following method of avoiding these instabilities. The beam current should be held below  $I'_{cr}$  until neutralization has been reached. After that the beam current can be increased without violating the condition

$$\beta(1 + \eta) < \eta^2$$

where  $\beta$  is the ratio of secondary to primary plasma electron densities. It is claimed that in this manner the beam current can be brought up to any desired value limited by the emissive properties of the cathode.

This method takes care of the hydrodynamic instability of the beam. It does not eliminate the possible kinetic instabilities appearing as intense noise. However, in the nonrelativistic case these instabilities are small, develop in a narrow region of phase velocities, and cannot disrupt the electron current in the beam. In the relativistic region, critical currents increase as the cube of energy [36], offering much better prospects for the production of very high currents.

In the monoenergetic approximation of relativistic beams, the critical current is determined by electrostatic instabilities. If in the nonrelativistic case, the limiting current of a neutralized beam is about six times larger than that of a beam in vacuum, the relativistic limiting current is larger still by a factor  $(E/mc^2)^2$ . However, it should be noted that such a rise in the current is possible only under conditions where the system does not develop a current-convective instability. In general, instability may develop at fairly low currents, even lower than the critical current in nonneutralized beams. With finite values of the magnetic field, it is fairly difficult to prevent the current-convective instability in a neutralized beam. Therefore, under actual conditions, it is much easier to obtain high currents in overneutralized electron beams when the beam passes through a very dense plasma. Rukhadze showed that the development of electron current-convective instabilities limiting the critical current is suppressed considerably in overneutralized beams.

Another advantage of overneutralized electron beam systems is based on the fact that, in the interaction of a relativistic electron beam with plasma, the relative loss of beam energy by excitation of oscillations is of the order of  $(E/mc^2) (n_b/n_p)^{1/3}$ . When this quantity is small, beam energy losses and the resulting dissipation of energy are negligible, so that, in spite of the fact that the conditions for instability development have been met in the system, very high currents can be reached without significant disruption of the beam. This illustrates the difference between critical and limiting currents: In the case of precisely neutralized beams, the

Buneman instability causes the beam to lose a considerable portion of its energy and to undergo significant changes, so that the critical currents are at the same time limiting currents. On the other hand, in overneutralized beams, the limiting currents can be higher than critical currents [37].

According to Rukhadze, the study of critical currents in beams passing through plasma-filled waveguides is prompted mainly by the problem of long-distance transport of the beam [37]. The general conclusions reached at the time of Rukhadze's statement were that an electron beam in plasma can be unstable at practically any current in the beam, however low, as soon as plasma density exceeds a certain critical value. On the other hand, if the beam density is much lower than plasma density and plasma density is lower than the referenced critical value, the electron beam in the plasma is always stable, and the dependence of the critical plasma density on beam current is very weak. Under these conditions currents in electron beams that can pass through dense plasma can be very high. Thus, for an electron energy of 5 MeV in an overneutralized beam that completely fills a waveguide, a current of  $10^6$  amperes can be readily obtained.

Further increases in relativistic limiting currents appear possible when we abandon the monoenergetic approximation and take into account the relativistic velocity dispersion that is generally present in real electron beams.

Investigation of the effect of relativistic and ultrarelativistic energy dispersion of particles on the stability of neutralized electron beams was begun only a year or two ago [41, 42]. Again, a metal waveguide and a strong axial magnetic field were postulated.

As long as  $\ln 2\gamma \lesssim 1$  (low axial energy region), the neutralized electron beams with ultrarelativistic energy dispersion can develop only kinetic instabilities similar to the ion-acoustic instability of current-carrying nonisothermal plasma. The frequency of the excited oscillations considerably exceeds their growth, and the ion  $\omega_L > \omega \gg \gamma$ . Therefore, such an instability cannot disrupt the current in the beam and dictate the critical current.

However, as electron energy increases and  $\gamma > 1.5$ , the kinetic instability becomes aperiodic and gradually transforms itself into a

hydrodynamic instability when  $\gamma \geq 2.5$ . The growth rate of the instability exceeds that of the ion  $\omega_L$ ; thus, the instability can develop in pulse systems as well. The critical current due to this instability is

$$I_{cr} = \frac{(2.4)^2 mc^3 \gamma^3 T_e}{4e(\ln 2\gamma - 1) mc^2}$$

where  $T_e \gg mc^2$  is the effective temperature characterizing electron energy dispersion. According to the above expression, the critical current of a beam with energy dispersion is larger than that of the monoenergetic beam by the factor  $T_e/mc^2$ . It is also concluded that the critical current in such beams can exist only if  $\gamma > 1.5$ . Below that energy, the beam can develop only kinetic instability incapable of limiting the current.

E. R. Harrison advanced the concept of slipping instability in electron beams (1963) in an infinitely strong axial magnetic field due to velocity dispersion of electrons in the beam. Since 1965, Rukhadze has been investigating this effect and the validity of Harrison's instability criterion. The discovery of a mathematical error in Harrison's work led Rukhadze to the formulation of new slipping instability criteria for electron beams having linear velocity profiles [43]. Thus, in an infinitely strong magnetic field, Rukhadze finds the beam always stable, and in zero field, always unstable. Insulating the beam from the metal wall of the waveguide stabilizes it against slipping instability to some extent, since in that case a larger velocity gradient is required for the instability to occur than in the case of an uninsulated beam [44].

The effect of instabilities on the critical current has also been investigated for the case of hollow beams [45]. Neutralized hollow beams were found to have a significant advantage over solid beams, since the critical currents are larger by the factor of the ratio of the external radius to the thickness of the tube wall formed by the beam. If such a ratio is 10 and electron energy is 5 MeV, the maximum current in a neutralized hollow beam may be of the order of  $10^8$  A. However, for long beams and weak external magnetic fields,

this advantage of hollow beams disappears because of current-convective instability, so that the limiting current in very long hollow beams may be lower than in solid beams.

Of special interest is beam behavior in plasma not confined to waveguides. The problem of magnetic neutralization of electron beams in such a case was considered extensively by Rosinskiy and Rukhlin [46]. In their analysis, they took issue with Hammer and Rostoker [47], who neglected the diffusion of magnetic field into the plasma. This effect tends to remove both magnetic and electrostatic neutralization of the beam at long distances from the injector. On the other hand, Rosinskiy and Rukhlin found that the metal waveguide practically does not affect the magnetic neutralization of high-current electron beams, making it possible to consider a theory of injection of such beams into spatially unbounded plasma [48]. Their interest in this problem was based on, according to their own statement, the recently begun experiments in artificial injection of electron beams into the ionosphere [49].

The steady-state behavior of a charged-particle beam injected along the magnetic lines of force in plasma whose density is much lower than the initial density of the beam is quite complex, even in the approximation of laminar flow (no intersection of the trajectories of individual particles in the beam). Given moderate beam energy and low external magnetic field, the beam can expand considerably as it travels in plasma, assuming the shape of a corrugated cylinder. If plasma is strongly magnetized, i.e.,  $\Omega \gg \omega_L$ , beam density is always larger than plasma density. In weakly magnetized plasma ( $\Omega \leq \omega_L$ ), the beam expands until its density falls below that of plasma and the beam becomes neutralized by plasma space charge. Under such conditions, the effect of the self-magnetic field can be neglected. This model of beam behavior remains valid for moderate departures from the assumption of zero energy dispersion and purely laminar flow. The initial thermal dispersion of beam particles affects their trajectories at some distance from the injector. As a result, the beam corrugations become smoother, with an average beam radius of the order of the maximum radius of the corrugated beam [49].

Experimental parameters for atmospheric sounding considered by this group are as follows: for electron beams --  $n_b \approx 10^4 \text{ cm}^{-3}$ ,  $I_0 \leq 1 \text{ A}$ ,  $E \approx 1 \text{ to } 10 \text{ MeV}$ , and  $r_0 = 10^2 \text{ cm}$ ; for ionospheric plasma --  $n_p \approx 10^5 \text{ to } 10^6 \text{ cm}^{-3}$ ,  $B_0 \approx 0.1 \text{ to } 0.5 \text{ Oe}$ , so that  $\omega_L > \Omega$  [50]. Under these conditions, instability oscillations occur in plasma only at the frequency  $\omega^2 \approx \Omega^2 + \omega_L^2 \approx \omega_L^2$ . The growth rate of the instabilities is a function of this frequency. In strongly relativistic beams the growth rate decreases as beam energy increases, while it is independent of energy in weakly relativistic beams. If instabilities are used to study ionospheric parameters, weakly relativistic or nonrelativistic beams are preferable [50].

#### D. BEAM-PLASMA INTERACTION

A separate research team within the Rukhadze group has been engaged since the mid-1960s in an effort to produce intense collimated rf radiation in the centimeter and millimeter ranges by passing high-current electron beams through plasma-filled waveguides. The team includes B. A. Aronov, L. S. Bogdankevich, M. Ye. Chogovadze, O. V. Dolzhenko, T. I. Kovtun, A. M. Rayzer, P. S. Strelkov, and I. I. Zhelyazkov. The membership of this team partially overlaps that of the group working with critical and limiting currents in electron beams, described in the preceding section. This overlap is to be expected, of course, since both subjects entail the study of basically the same phenomena. However, there is a sharp contrast in the purpose of these two activities: While the research reviewed in the preceding section was aimed at the retention of the energy in the beam and the preservation of its integrity, the research described in the present section explores the conditions for the most efficient transfer of beam energy to the plasma.

The purpose of this research effort, explicitly stated in a number of Soviet papers, may be summarized as follows: The generation and amplification of high-power microwave radiation is one of the most interesting current applications of electron beams, the aim of which is to excite electromagnetic oscillations in plasma by developing beam instability [50, 51, 52, 53]. And while the explicit goal of the bulk



of the research is to produce intense collimated bursts of microwave energy, the problem of preserving the integrity of the electron beam in the face of the variety of possible beam and plasma instabilities is not absent from the minds of Soviet researchers. Bogdankevich, Zhelyazkov, and Rukhadze noted, for example, that "Obviously, of the greatest interest here is the transport of the electron beam over a long distance" [54], indicating that they were concerned also with the instabilities in infinitely long waveguides.

The material on beam-plasma interaction contained in the research papers published by members of the team does not appear complete enough for us to reach any conclusions about the results achieved to date by the Soviets in this effort. It is not clear whether the ambiguity is due to a deliberate withholding of information, or to a failure to advance in the research. Most of the published papers, and especially those published recently, are theoretical and far removed from the stage of possible practical application. On the other hand, the authors state explicitly that their findings indicate the practical feasibility of intense microwave plasma sources in the centimeter and millimeter wavelength ranges. What is revealed by an analysis of the Soviet papers, however, is the comprehensive approach to the problem and the sustained effort maintained over a number of years.

A series of experiments on the generation of microwaves by an electron beam in plasma was performed with modest input powers [55, 56] in the early stages of the research. The primary aim of these experiments was to determine the critical plasma density,  $n_{cr}$ , above which instabilities occur and microwave emission is observed. The experiments were based on the following theoretical model of the beam-plasma interaction process:

A metal waveguide filled with neutral gas and placed in a uniform external magnetic field  $B_0$  is postulated. An electron beam of radius  $r$  coaxial with the waveguide of radius  $R$  passes through the gas. The beam ionizes the gas in a time longer than the beam-plasma interaction time. If the neutral gas density is above a critical value, plasma density increases linearly with time until  $n_{cr}$  is reached and a burst of electromagnetic oscillations is observed at a frequency of



$\omega \ll \Omega_e$  ( $\Omega_e$  is the electron cyclotron frequency). If the beam current  $I < I_0$ , where  $I_0$  is the limiting vacuum current, ionization continues until plasma density exceeds  $n_{cr}$  by an order of magnitude, and microwave oscillations appear at  $\omega \lesssim \Omega_e$ . If  $I > I_0$ , plasma density at first linearly reaches a plateau near  $n_{cr}$ , accompanied by the low-frequency oscillations, and then jumps two orders of magnitude above  $n_{cr}$  where 100 percent ionization is achieved and strong microwave emission is observed.

The above model has been considered for a heavy gas, such as krypton, in which all oscillatory processes are faster than the ionic cyclotron frequency:  $\Omega_e \gg \omega \gg \Omega_i$ . The model also postulates the absence of secondary electrons that, unless removed, can reach a density of  $0.5 n_b$ . The presence of secondary electrons can disrupt the linear growth behavior of plasma density below  $n_{cr}$ .

The theoretical value of the critical plasma density that served as the reference value in the experiments is given by

$$n_{cr} = \frac{\mu v^2}{3 \times 10^9 r^2} \left\{ \left[ 1 + \left( \frac{n_b}{n_p} \right)^{1/3} \right]^3 - \frac{\mu^2 v^2}{r^2 \Omega_e^2} \right\}^{-1}$$

where  $\mu = 2.4$  (root of Bessel function). After  $n_{cr}$  is reached, the system produces axially symmetric oscillations. In the experiments, the observed values of  $n_{cr}$  were in general agreement with the above relation, except that the experimental data showed a strong dependence on beam current. The difference between experimental and theoretical values was most pronounced at low current values. The actual numbers involved in the experiments were as follows: The electron gun consisted of a 3-cm-plane lanthanum hexaboride cathode 0.5 cm away from a mesh anode of 70 percent transparency. The electron beam was 10 kV, 10 A, 500  $\mu$ sec pulse, 2.7 cm in diameter in a 4 kOe field, injected into a 55-cm or 35-cm drift tube filled with krypton. Measured microwave output power was over 80 W at 3300 to 2100 MHz, yielding less than 0.1 percent efficiency.

The experimental effort was followed by a series of theoretical analyses of the problem of critical plasma density and the associated

types of instabilities. At first, an attempt was made to develop a linear theory applied to electrostatic longitudinal oscillations in space-bounded plasma, i.e., in plasma confined by waveguides [50, 54].

The linear theory yields the value of critical current  $I_{cr}$  in a relativistic beam that can be passed through a waveguide completely filled with plasma ( $r = R$ ) that is denser than the beam as

$$I_{cr} < \frac{(2.4)^2 m v^3}{4e(1-\beta^2)^{3/2}} \approx 10^{-27} \frac{v^3}{(1-\beta^2)^{3/2}} \text{ A}$$

where  $\beta = v/c$ .

The critical current can thus be assumed to vary as the cube of beam energy, and for  $E = 5 \text{ MeV}$ ,  $I_{cr} < 3 \times 10^7 \text{ A}$ . If  $r < R$ , the critical current is an order of magnitude lower, but its behavior as a function of  $v^3$  is valid only in the relativistic region; for  $R/r \sim 10$ , it is valid for  $E \gtrsim 1 \text{ MeV}$  [57].

Linear analysis applied to the concept of instability consisting of purely longitudinal waves in plasma was later found to be an excessively loose approximation of the real conditions in plasma-filled waveguides. The most significant instabilities occurring in the process of interaction between high-current electron beams and plasma in metal waveguides and an external magnetic field are of two types [58]:

1. An almost transverse aperiodic instability analogous to the hydrodynamic instability and causing filamentation of plasma.
2. Quasi-longitudinal waves.

The hydrodynamic instability is caused by a nearly monoenergetic low-density electron beam. A single-mode instability is excited, since only the mode with the maximum growth rate is assumed. The analysis of the hydrodynamic instability requires the development of nonlinear theory [59].

However, under the physical conditions postulated for this study, the growth rate of the second type of instability, i.e., the quasi-longitudinal waves, is always faster than that of hydrodynamic instability. Long systems excite a broad spectrum of waves, and the

single-mode approximation is not valid. A quasi-linear approximation becomes necessary for analysis [58].

The frequency spectrum of such an instability is shown in Fig. 9.

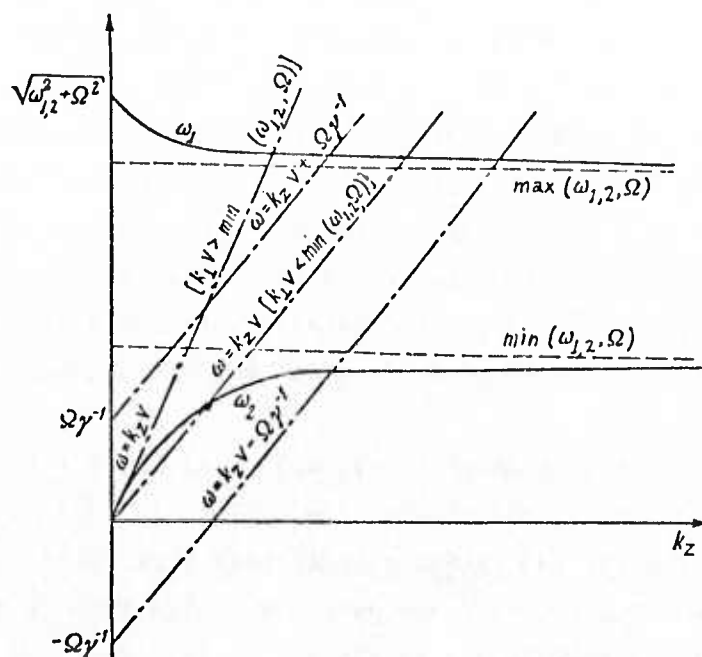


Fig. 9 -- Frequency spectrum of longitudinal instability [51]

The natural oscillation frequencies,  $\omega_1$  and  $\omega_2$ , in plasma can be represented by the spectrum [51]

$$\omega_{1,2}^2 = \frac{1}{2} \left[ \omega_L^2 + \Omega^2 \pm \sqrt{(\omega_L^2 + \Omega^2)^2 - 4 \frac{k_z^2}{k_1^2 + k_z^2} \omega_L^2 \Omega^2} \right]$$

where  $k_z$  and  $k_1$  are the longitudinal and transverse wave numbers respectively.

Strong beam-plasma interaction with growing instability occurs at the intersection of the  $\omega_{1,2}$  lines with the straight-line plots of

$$\omega = k_z v \text{ and } \omega = k_z v \pm \Omega \gamma^{-1}$$

The instability at the intersection of  $\omega = k_z v$  with  $\omega_{1,2}$  is called the Cherenkov type; that occurring at the intersection of  $\omega = k_z v \pm \Omega \gamma^{-1}$  with  $\omega_{1,2}$  is the cyclotron instability.

The graph shows that for  $v > R/2.4 \text{ min } (\omega_2, \Omega)$  Cherenkov instability is possible only in the upper plasma frequency  $\omega_1$ ; for  $v < R/2.4 \text{ min } (\omega_2, \Omega)$ , Cherenkov instability can occur at both  $\omega_1$  and  $\omega_2$ . However, in dense plasma, when  $\omega_L \gg \Omega$ , only  $\omega_1$  is excited and equals  $\omega_L$ . In dense plasma, cyclotron instability also occurs at  $\omega_1$ , but Cherenkov instability predominates. Cyclotron instability is unlikely at  $\omega_2$ . This theory is valid for the case of electrostatic approximation of strictly potential waves; it is said to hold reasonably well also for the realistically obtainable case of Cherenkov excitation of Langmuir frequencies, which appear as near-potential waves.

Given an electron beam of 1 MeV, 1.5 to 15 kA,  $R = 1 \text{ cm}$ , and  $n_b \approx 10^{11}$  to  $10^{12} \text{ cm}^{-3}$ , and plasma of  $n_p \approx 10^{15}$  to  $10^{13} \text{ cm}^{-3}$ , the wavelength of the excited plasma oscillations lies within  $\lambda_0 = 0.1$  to  $1 \text{ cm}$ , while  $\omega = \omega_L$ . For these parameters,  $2.4 v/R\omega_L \lesssim 1/2$ . The instability growth rate is  $\delta = (n_b/2n_p)^{1/3} \omega_L/\gamma$ . For  $n_p = 10^{15} \text{ cm}^{-3}$ ,  $n_b = 10^{12} \text{ cm}^{-3}$ ,  $I = 15 \text{ kA}$ ,  $\lambda_0 = 0.1 \text{ cm}$ , the bandwidth is  $\Delta\lambda_0/\lambda_0 = 0.02$  and  $\delta = 4 \times 10^{10} \text{ sec}^{-1}$ . This kind of instability is obtained with  $B \lesssim 5 \text{ kOe}$ .

In rarefied plasma or strong  $B$ ,  $\omega_L \ll \Omega$ , the lower Langmuir region is excited and longer wavelengths are obtained. For  $n_p \approx 10^{13} \text{ cm}^{-3}$ , and  $n_b \approx 10^{11} \text{ cm}^{-3}$ , with  $I = 1.5 \text{ kA}$  and  $\lambda_0 = 1 \text{ cm}$ ,  $\Delta\lambda_0/\lambda_0 \approx 0.05$  and  $\delta = 10^{10} \text{ sec}^{-1}$ . The authors are satisfied that these results show that narrow-band centimeter and millimeter oscillators are feasible [51, 60, 61].

The analysis discussed thus far has dealt with bulk waves in metal waveguides where the electromagnetic energy was generated in the interior of the plasma. Under such conditions, the near-potential waves had the highest growth rate: The electromagnetic radiation was due to the small transverse component (nonpotentiality) of the plasma waves. A different situation occurs when the metal waveguide wall is at some distance from the plasma surface. The electron beam

then excites mainly surface waves whose potentiality depends on beam velocity. Nonrelativistic beams excite surface oscillations that are nearly potential, while relativistic beams excite strongly non-potential waves. The most recent work of this research group deals with the two cases of surface wave generation by nonrelativistic and relativistic beams.

In the first case, a nonrelativistic monoenergetic beam with radius  $r_0$  passes through plasma bounded by vacuum or a dielectric surface. The beam and plasma dimensions are considered to coincide. Under these conditions the beam is found capable of exciting surface oscillations in plasma, primarily in the axially-symmetric modes. Analysis of quasi-linear relaxation of the hydrodynamic beam instability for these modes shows that the energy of steady-state oscillations in plasma is of the order of  $(n_b/2n_p)^{1/3}$  of the initial beam energy. When the plasma density is much higher than beam density,  $n_b/n_p \ll 1$ , the energy loss of the electron beam is expended mainly on setting up an electric field in plasma [52].

In the case of relativistic beams exciting surface waves in plasma (the metal waveguide wall is sufficiently far away from the plasma surface), the latter are strongly nonpotential. In dense plasma, such an electron beam excites shortwave surface oscillations whose growth rate is the same for any type of axial modes. In rarefied plasma, only longwave oscillations having mainly axially asymmetric modes, are excited.

Computation of the power of the resulting rf emission and the efficiency of such a surface-wave oscillator indicates a significant difference between the two cases of nonrelativistic and relativistic electron beams. In the first case, the rf radiation flux directed outward from plasma surface equals that directed towards the plasma interior. In the second case, the outward flux is  $\gamma^4$  times greater than the inward flux.

In the relativistic case, the efficiency of conversion of beam energy into rf radiation (outward flux, dense plasma) is given by

$$\eta_{\text{rel}} = \frac{1}{16} \frac{v^2}{c^2} \frac{v}{r_0 \omega_L}$$

The conversion efficiency of nonrelativistic beams under the same condition is

$$\eta_{\text{nrel}} = \frac{1}{32} \left( \frac{n_b}{2n_p} \right)^{1/3} \frac{v}{r_0 \omega_L}$$

Since  $n_b/n_p \ll 1$  and in the relativistic case  $v/c \approx 1$ , the conversion efficiency of relativistic beams is much greater [53].

The foregoing analysis, case A, was based on the assumption that the free-surface plasma cylinder was confined by a relatively weak magnetic field whose effect on either plasma or electron beam could be neglected in the interaction theory, so that

$$\omega_{LP} \left( \frac{n_b}{n_p \gamma} \right)^{1/3} \gg \Omega$$

In case B [62], this assumption was modified by postulating that the external magnetic field can "magnetize" the beam but not the plasma:

$$\omega_{LP} \gg \Omega \gg \left( \frac{n_b}{n_p} \right)^{1/3} \frac{1}{\gamma} \omega_{LP}$$

Here  $\omega_{LP}$  is the Langmuir frequency of plasma electrons. Under this condition, the beam-plasma interaction is of the Cherenkov type (see above), so that  $\omega = k_z v$ , and the cyclotron mechanism need not be considered. The results of the interaction depend on plasma density. If plasma is dense, the analysis shows that a large number of short-wave azimuthal modes of surface waves are excited. On the other hand, in low-density plasma, only a single longwave axially symmetric mode can be excited. This is the basic difference between case A and case B, since in case A a large number of azimuthal modes can be excited even in low-density plasma.



Computation of the Poynting vector for case B yields the expression for the efficiency of conversion of beam energy into rf energy, which is less than 0.1 percent for a nonrelativistic beam and about 1 percent for a relativistic beam.

#### E. MICROWAVE GENERATION BY ELECTRON BEAM IN VACUUM

The problem of producing microwave emission from high-current electron beams interacting with periodic spatial structures rather than with plasma has been studied by Rukhadze's group to a limited extent. This work appears to be pursued in association with the Scientific Research Institute for Radiophysics, where A. V. Smorgonskiy, M. I. Petelin, and others have been developing the theory of microwave oscillators based on such an interaction.

The idea of using fast electron beams drifting in spatially periodic fields to generate centimeter-to-visible-wave radiation is attributed to V. L. Ginzburg. This idea found an application in the undulator and the ubitron (Enderby and Phillips) capable of delivering 150 kW at 54 GHz and 1600 kW at 16 GHz for a 70-kV beam. According to Petelin and Smorgonskiy [63], further increases in the power output of these devices are now possible, thanks to the development of MV electron beams. The authors at the Radiophysics Institute developed the nonlinear theory of the O-type ubitron, in which the electron beam moves through a static configuration of the magnetic field. It is assumed here that the space charge of the beam can be neglected and that the electrodynamic system of the ubitron can be regarded as a high-Q cavity. The optimal theoretical efficiencies of the system are found to be as follows:

- o Case A -- constant rf field intensity
  - weakly relativistic electron beams,  $\eta = 30$  percent
  - ultrarelativistic electron beams,  $\eta = 55$  percent
- o Case B -- linearly increasing rf field intensity
  - weakly relativistic electron beams,  $\eta = 20.5$  percent
  - ultrarelativistic electron beams,  $\eta = 45$  percent



A 20 percent velocity spread present in real electron beams will lower these efficiencies to 85 percent of the above values.

On the basis of this analysis, its authors concluded that both the weakly relativistic and the ultrarelativistic electron beams can be used effectively in ubitrons, whose basic advantages are the relatively high efficiency and a low sensitivity to the quality of the beam, i.e., its energy spread.

The monotron, which is a single-cavity ubitron, has been theoretically analyzed for a high range of rf-field intensities (not specified) where its efficiency was estimated at  $\eta = 20$  percent [64].

Experimental work on electron beams interacting with spatially periodic fields is being performed at the Lebedev Physics Institute. A single report available so far [65] describes a simple device utilizing the Cherenkov emission principle in which a straight-line electron beam interacts with a synchronous spatial harmonic of an electromagnetic wave whose group velocity is opposite to the direction of the electron beam. A schematic diagram of the oscillator is shown in Fig. 10.

The electromagnetic wave with the necessary dispersion and polarization characteristics was formed in the corrugated waveguide. The electron beam was produced by a 600-keV, 20-kA, 20-nsec accelerator of the Lebedev Physics Institute [5]. The beam was focused by a quasi-stationary field of the pulsed solenoid (5) which varied from 2 to 5 kOe. Since it was desirable to let the radiation out in the direction of the beam, the interaction region, represented by the corrugated waveguide, was separated from the acceleratory by a constriction (3) blocking the  $E_{01}$  working mode. After reflection from the constriction (3), the wave passed through the system, no longer interacting with the beam, to be emitted by the horn (9). The vacuum in the system was  $2 \times 10^{-5}$  torr. The beam electron energy was  $670 \pm 70$  keV. On the output side, the emitted wavelength was  $3.1 \pm 0.1$  cm, and pulse length at half power was 10 nsec. The experimental value of maximum efficiency of electron energy conversion to electromagnetic radiation was  $\eta = 12$  to 15 percent.

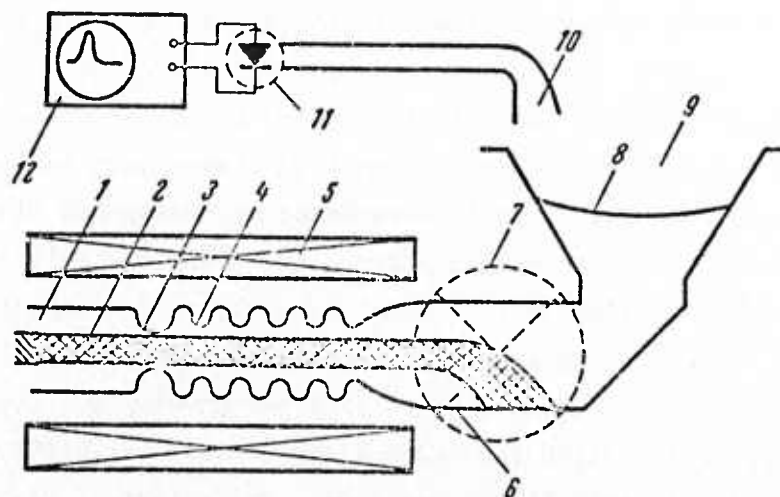


Fig. 10 -- Experimental oscillator at the Lebedev Physics Institute [65]

- 1 - accelerator
- 2 - electron beam
- 3 - constriction
- 4 - corrugated waveguide
- 5 - pulsed solenoid
- 6 - matching stub
- 7 - deflecting solenoid
- 8 - mica window
- 9 - horn
- 10 - receiving horn
- 11 - germanium detector
- 12 - oscilloscope

#### F. SOLID-STATE PLASMAS

The problem of generating powerful microwave beams from electron beam interaction with plasma is also being pursued by considering electron-hole plasmas in semiconductors and semimetals. The team active in this area since the early sixties includes S. P. Bakanov, L. S. Bogdankevich, R. R. Kikvidze, and V. G. Koteteshvili.

The published reports on this subject have been entirely theoretical, although reference is made to experiments some of which could have been Soviet.

The early theory [66, 67, 68] was drawn from that for weakly-ionized gaseous plasma; it showed that low-frequency oscillations of solid-state plasma can be excited at relatively low carrier velocities

that are below the thermal velocities. However, the theory was based on the invalid assumption that the energy and momentum relaxation time and the effective mass are independent of carrier velocity, i.e., of the electric field. This assumption led to the erroneous conclusion that the excitation is possible only in plasma with two species of carriers [69]. The velocity-dependence of relaxation time later became the basis of studying electrostatic (longitudinal) oscillations of solid-state plasma with a small population of a single species of carrier. Under these conditions, inhomogeneous plasma placed in parallel electric and magnetic fields can develop two types of instability: one is called the current-convective instability by this team, spiral instability by Glicksman [70], gradient instability by Gurevich and Ioffe, and temperature instability by Tsendin. This type of instability is due to inhomogeneity of the plasma; the other type is due to negative volt-ampere characteristic of the carrier current.

In the model developed by Rukhadze's team, electron collisions are neglected and only lattice scattering is taken into account. The negative volt-ampere slope is theoretically possible in this model only if due to the velocity-dependence of relaxation time, since recombination at impurity levels, another possible cause of the negative slope, is considered negligible.

The current-convective instability is found to predominate for modes propagating at large angles to the magnetic field in plasma with the following parameters: carrier velocity  $\geq 10^7$  cm/sec, Larmor frequency  $\Omega = eB/mc \sim 10^{11}$  to  $10^{12}$  sec<sup>-1</sup>, momentum-to-energy relaxation time ratio of  $\sim 10^{-4}$ , and a typical inhomogeneity size of  $10^{-1}$  cm. The development of this type of instability is more probable than that due to the negative slope, since the growth rate of the former exceeds that of the latter [71]. In a strongly magnetized solid-state plasma with a small carrier population, the current-convective instability is the only possible instability type if plasma is inhomogeneous and unbounded or homogeneous but bounded. The current-convective instability can be an order higher in the magnitude of frequency and growth rate than that occurring in spatially homogeneous unbounded plasmas due to the negative volt-ampere characteristics [69].

However, the instability due to negative volt-ampere characteristics has been significant in the search for plasma-generated microwave sources ever since the discovery of the Gunn effect in 1963. The departure from Ohm's law of the characteristic is made possible by the heating of electrons in a semiconductor placed in an electric field. The resulting instability spontaneously generates electromagnetic oscillations.

A specific analysis of electron beam-plasma interaction in solid-state systems was reported in [72], which postulated a semiconductor with a cylindrical hole through which a nonrelativistic monoenergetic electron beam is passed. The electron scattering neglected in the previous states of research must now be taken into account to determine the threshold current of the beam, a quantity that is very high in real semiconductors. In fact, Rukhadze comments that this may be the reason why experiments have so far failed to produce rf excitation in the interaction between electron beams and solid-state plasma. He also considers at this point the excitation of surface, rather than bulk, waves for the same reasons as in the case of gaseous plasmas discussed in the preceding section.

The proposed narrow-band microwave oscillator must satisfy the condition  $\delta < \nu$ , where  $\delta$  is the instability growth rate and  $\nu$  is electron collision frequency. The bandwidth depends on  $\delta$  and can be much narrower than  $\nu$ . As a specific example, Rukhadze considers a specimen of InSb at 77° K, generating at the frequency of  $\omega = 2 \times 10^{12} \text{ sec}^{-1}$ . For a specimen length of 1 cm and carrier density of  $n_p \approx 5 \times 10^{14} \text{ cm}^{-3}$ , the threshold current density required to excite oscillations in solid-state plasma is of the order of  $j = 30 \text{ A/cm}^2$ . The growth rate of oscillations rises with increasing current density and at  $j = 100 \text{ A/cm}^2$  reaches  $\delta = 4 \times 10^{10} \text{ sec}^{-1}$ . Therefore the bandwidth is  $\Delta\omega/\omega \approx \delta/\omega \approx 2$  percent. An effective beam radius should be of the order of  $2 \times 10^{-2} \text{ cm}$  for a 200-keV beam; the current thus is 0.3 A, and power is  $6 \times 10^4 \text{ W}$ . According to theory, the power of the generated longitudinal waves then is 100 W. About 10 percent of this output power can be converted to transverse oscillations capable of leaving the crystal [72].

Since purely longitudinal (electrostatic) oscillations generated by an electron beam passing through a cylindrical hole in a semiconductor or semimetal remain for the most part locked in the solid-state plasma, the effectiveness of such a system as an rf oscillator depends on its capability to emit nonpotential modes. Again, in his attempt to evaluate this capability, Rukhadze draws on the analogous theory developed for gaseous plasma. He concludes that the mode generated by the above system can be considered potential only if one neglects the small term  $v/c \ll 1$ . Actually it is a quasi-potential mode for which in the absence of an external magnetic field  $B_\varphi \sim (v/c)E_2$ . The frequency and growth rate of this mode are the same as those determined under the assumption of purely potential modes. However, the quasi-potential mode can be emitted and propagated outside the system.

The efficiency of electron beam energy conversion to quasi-potential mode energy decreases as  $\omega_0 a/v$  ( $a$  is the radius of the semiconductor channel) increases in the shortwave region ( $\omega_0 a/v > 1$ ), or region of low-density plasma. The efficiency also decreases in the longwave region ( $\omega_0 a/v < 1$ ) with decreasing  $\omega_0 a/v$ ; it thus approaches a maximum for  $\omega_0 a/v \approx 1$  [73]. These relationships are valid in the absence of an external magnetic field. In the case of an external magnetic field focusing the beam, the conversion efficiency in low-density plasma is lower than in the absence of magnetic field. In high-density plasma, the opposite is true; magnetic field increases efficiency. The efficiency of a realistic oscillator of such a type can reach 3 to 5 percent [74].

The system considered here generates surface waves in plasma. In theoretical systems generating quasi-potential bulk waves, the expressions for electromagnetic energy flow and conversion efficiency contain a small term of the order  $(n_b/n_p)^{1/3}$ . This term is absent in the analogous expressions for the surface wave system, indicating, according to Rukhadze, the superiority of this system as an oscillator of high-power centimeter and millimeter emission [73].

### G. PINCH DISCHARGE AS A LASER PUMP SOURCE

A separate project has been pursued by Rukhadze at the Moscow State University to develop an exploding wire technique for ultra-violet pumping of high-power lasers. The team engaged in this project includes A. F. Aleksandrov, V. V. Zosimov, V. I. Savoskin, I. B. Timofeyev, B. P. Kaminskaya, Yu. P. Popov, and S. P. Kudryumov.

The project was initiated in response to a specific need for high-power optical pump sources in the region of 2000 to 3000 Å [75, 76]. A promising solution to this problem was seen in the high-current pinch discharges in atmospheric gas or in vacuum, which could be used to drive various active laser media in the gaseous, liquid, and solid states. Research in this area performed previously in connection with controlled fusion reactions showed that sausage and hose instabilities of the pinch disrupt the discharge in a few μsec. However, radiative discharges in heavy-element plasma with a temperature of 2 to 5 eV and density of  $10^{18}$  to  $10^{20}$  cm<sup>-3</sup> have a duration of 30 to 100 μsec, which is at least an order of magnitude longer than the laser pump time requirement.

The laser pump requirement imposes the following conditions on the pinch discharge: plasma radiation should approximate black body radiation; the temperature should be homogeneous throughout the discharge region; and the ratio of light output energy (efficiency) to electric input energy should be optimal. These requirements limit the total discharge current to a certain range:

$$I_{\min} \leq I \leq I_{\max}$$

The lower limit stems from the postulate that the characteristic dimension (radius) of the discharge be much greater than the Rosseland photon interaction length, while the upper limit is obtained by equating the characteristic dimensions of thermal and density inhomogeneities in the discharge. For a Z-pinch in plasma derived from multiple ionized atoms (silver, tungsten, lead, aluminum, etc.)  $I_{\min} \approx 100$  to 130 kA and  $I_{\max} \approx 420$  to 430 kA [76, 77].



For currents below  $I_{\min}$ , the discharge is transparent and therefore subject to fast thermal instability, while above  $I_{\max}$  the efficiency of the radiator drops sharply due to thermal inhomogeneities of plasma. Within these two limits the plasma has a high thermal conductivity and its temperature is homogeneous over its cross-section. Such a plasma radiates as an absolute black body; i.e., its maximum radiation output is independent of frequency.

It would seem that such an "opaque" discharge would be optimal for use as a laser pump and superior to a transparent discharge in view of the thermal instability of the latter. However, an optically opaque discharge has a low conversion efficiency in the region of special interest, 2000 to 3000 Å. A black body emits in this region about 6 percent of its total radiation at a temperature of 3 to 5 eV. Therefore, the optimal choice would be a "gray" radiator similar to the black body in the specified spectral range and transparent in the range of shorter wavelengths. At the same time, the longer wavelengths could be expected to provide the thermal conductivity necessary to eliminate thermal instability.

The ratio of radiation flux from a gray discharge to that from an opaque discharge depends on the discharge current. When current is high, i.e., close to  $I_{\max}$ , a gray discharge behaves like a black body. At low currents close to  $I_{\min}$ , the efficiency of a gray discharge is approximately 3 times that of an opaque discharge [78].

So far, only linear pinches in transparent plasma have been subjected to thorough experimental investigation. A particularly noteworthy study was performed with transparent discharges in lithium plasma by a group at the Lebedev Physics Institute consisting of V. B. Rozanov, A. D. Klementov, G. V. Mikhaylov, F. A. Nikolayev, Yu. P. Sviridenko, and A. A. Vekhov. This group does not appear to be a part of Rukhadze's team. Its studies included determination of the absorption coefficients of the total output, spectral composition of the emission, spatial distribution of the parameters, energy balance, and stability of the discharge. While its results did not provide a direct proof that transparent discharges are subject to fast thermal



instability, they nevertheless indicated that such discharges have a complex irregular structure which precludes their use as laser pumps.

Outside of the work of his group, Rukhadze knows of no systematic study of opaque pinch discharges in heavy gas. In the foreign literature, only L. Niemyer [79] has shown that discharges in indium and aluminum vapor contain regions with homogeneous distribution of temperature that exhibit black body radiation in the quartz transmission band. However, Niemyer's data are inadequate, according to Rukhadze, for either a theoretical verification of the mechanism of pinch discharge in opaque plasma, or an application of such discharges to laser pumping.

Rukhadze's group has been interested since the mid-sixties in opaque plasma as a medium for high-current pinch to serve as an effective pump light source [80, 81, 82]. Systematic experimental work has been carried on for the past 3 to 4 years.

Experiments in vacuum [77] involved silver wires 50 cm long, 0.09 mm and 0.38 mm in diameter, exploded by 15- to 30-kV, 400-kA, 25- $\mu$ sec pulses in  $10^{-4}$  mm Hg. The results showed that the discharge contains a stage during which brightness temperature is independent of wavelength. This, in turn, means that there is a critical current value,  $I_{\min}$ , above which the discharge behaves like an absolute black body. The value of  $I_{\min}$  was found to be in good agreement with the theoretical values discussed above, and to be independent of the charging voltage and wire diameter, and thus of the number of particles in the discharge. The conversion efficiency in the ultraviolet region under optimal conditions when  $I \approx I_{\min}$  was found to be 4 to 5 percent [76, 77].

High-current discharges were also studied in atmosphere air [83]. Here, silver wire 8 cm long and 0.009 mm in diameter was exploded by 15-kV, 175-kA, 20- $\mu$ sec pulses. The discharge was found to be free of instabilities during the initial expansion stage, where the linear theory can be used with adequate approximation. During the magnetic confinement stage, however, the linear theory no longer holds, and the discharge radiates as a black body. Its conversion efficiency is the same as that of vacuum discharge. An explosion of a wire 75 cm long

provided an absolute yield of 9 kJ in the ultraviolet (2200 to 2700 Å) in 60 μsec [76].

The gathered experimental evidence and the theoretical considerations show that explosion of wires in atmospheric air produces a long-duration stable discharge. The temperature of the emitting surface varies with the discharge current from 1.5 to 2 eV during the main stage of the process corresponding to the first half-period of the discharge current. Under the given experimental conditions, about 70 percent of the stored energy is converted into discharge energy, and over 45 percent of the stored energy is converted into light [75]. Other materials used in these experiments, including aluminum, copper, and tungsten, yielded similar results. It is concluded that the equilibrium characteristics of the discharge and the opaque region are independent of plasma material. The discharge temperature increases with increasing current and decreasing total number of particles per unit length of wire. The duration of the discharge is determined by the surface mode of constriction instabilities, whose growth rate depends on the velocity of sound.

The preferred type of discharge for laser pump application thus is based on the vapor of the heavy elements; the current is near the lower limit of 100 kA, and the necessary brightness temperature is obtained by varying the total number of particles in the discharge. Table 4 shows the characteristics of the electric heavy-element wire explosions in air and vacuum as candidates for laser pumps compared to those of standard pump sources and lithium wire explosions. The data show that discharges in heavy-element vapor are at least as good as those in lithium. Furthermore, they have about the same efficiency in the ultraviolet as ordinary xenon lamps, but a much higher brightness which, for the same geometry, yields an order higher radiation output. Further increases of the absolute radiation output and duration of stable discharge will be sought in the coaxial reverse current discharges (reverse pinch). Estimates show that this may increase the absolute output by one or two orders in comparison to the output from the linear pinch [75, 84, 85].

Table 4

## COMPARISON OF LASER PUMP SOURCES

Operating Characteristics	Flash Lamps		Exp l o d i n g W i r e S o u r c e s	Heavy Element Wires				
	IFP-5000	UF 900/200 <i>Soviet</i>		Lithium in Air	Air, 20 kV	Air, 24 kV	Vacuum, 15 kV	Vacuum, 17 kV
Length of discharge, cm	25	90	14.5	75	75	40	96	
Stored energy, E, kJ	5	20	26.5	58	83	56	72	
Total energy delivered to discharge, $\alpha$ , kJ	4	16	17.5	35	60	38	51	
Peak brightness temp., °K	9,000	11,000	17,000	21,000	26,000	26,000	24,000	
Total radiation energy, W, kJ	2.6	-	6.7	26	38	20	29	
Radiation energy in interval $2200 < \lambda < 2700 \text{ \AA}$ , $W_{uv}$ , kJ	0.2	1.0	1.03	2.2	4.4	3.1	2.9	
Conversion efficiency, W/E, %	50	-	25	45	45	36	40	
Ultraviolet conversion efficiency, $W_{uv}/E$ , %	4	5	4	4	5	5.5	4	

#### IV. THE FAYNBERG GROUP

##### A. INTRODUCTION

The well-known research group headed by Ya. B. Faynberg at the Physicotechnical Institute of the Ukrainian Academy of Sciences in Khar'kov is one of the largest of those engaged in the study of beam-plasma interaction processes. Its main interest and work can be characterized in general as based on the principle of collective acceleration of charged particles. The subjects of study reflect either an attempt to clarify the mechanism of collective acceleration or the development of methods for practical application of this mechanism. Faynberg's group appears to be associated with applications to obtain controlled thermonuclear reactions to a lesser extent than the other groups discussed in this paper. In the area of practical applications, Faynberg devotes a major effort to the study of microwave plasma oscillators, the production of high-current electron beams in induction accelerators based on the linear plasma betatron, and the use of electron beams as laser pumps. However, the theoretical foundation of Faynberg's work is highly relevant to fusion research, and his group has maintained close contact with such fusion research leaders as Ye. K. Zavoyski, B. B. Kadomtsev, and R. Z. Sagdeyev for the review of individual papers.

The group leadership is as follows:

##### *Guidance and Support*

Ya. B. Faynberg

V. I. Kurilko

##### *Review*

Ya. B. Faynberg

L. I. Rudakov

V. I. Kurilko

B. B. Kadomtsev

Ye. K. Zavoyskiy

R. Z. Sagdeyev

A. A. Vedenov

K. D. Sinel'nikov (before 1966)

N. A. Khizhnyak (before 1966)

*Senior Authors*

## Beam-Plasma Interaction Stability and Microwave Oscillators

Ya. B. Faynberg

V. I. Kurilko, theoretician

V. D. Shapiro, theoretician

V. I. Shevchenko, theoretician

V. A. Buts, theoretician

Yu. V. Tkach, theoretician

L. I. Bolotin, experimentalist

A. K. Berezin, experimentalist

## Linear Plasma Betatron

Ya. B. Faynberg

L. I. Bolotin

Ye. I. Lutsenko

## Laser Pump

Ya. B. Faynberg

L. I. Bolotin

B. THEORY OF BEAM-PLASMA INTERACTION

The primary concern of the Faynberg group is the application of plasmas to the acceleration of charged particles. There are several distinct approaches to this problem, most of which derived from the now classic concept developed by V. I. Veksler, which opened up the possibility of coherent acceleration involving high electric field intensities, acceleration of quasi-neutral bunches, and acceleration of heavy particles indirectly by means of electrons which in turn are accelerated by rf fields.

One variant of the coherent method, the radiative acceleration of plasma, was developed by M. S. Rabinovich at the Lebedev Physics Institute (experimental and theoretical research) and by M. L. Levin at the Radio Engineering Institute, Academy of Sciences, USSR (theoretical research). Another approach, proposed by G. I. Budker, involved self-stabilization of electron-ion beams.

The principal approach developed by Faynberg is based on the acceleration in plasma of charged particles by longitudinal waves excited by electron beams. Faynberg was for a long time concerned with the fact that high-current accelerators of heavy particles and electrons required new methods of linear acceleration [86]. In linear accelerators, the increase in energy is possible only by increasing the accelerating field intensity or by increasing the length of the machines. Increasing the field intensity in conventional systems, however, renders the rf power losses prohibitive; increasing the length is not readily feasible. The basic problem underlying these limitations is the conventional use of metal waveguides in the accelerating systems. The metal wall of the waveguides absorbs a considerable portion of the electromagnetic energy. The most promising solution of this problem is to eliminate metal waveguides and accelerate electrons with electromagnetic fields propagating in media that allow for high-intensity electric fields with low rf energy loss.

Electron-ion plasma and unneutralized electron and ion beams constitute such media. They permit the achievement of a simultaneous axial and radial stability necessary to obtain high field intensities with reasonable energies and losses. These conditions can be obtained only when the input energy is concentrated in small volumes around the particles being accelerated.

Relatively low-density ( $10^9$  to  $10^{13}$   $\text{cm}^{-3}$ ) plasma can sustain waves with a high electric field intensity of the order of MV/cm. Increasing the plasma density shortens the wavelength and increases  $E_{\text{max}}$ .

The plasma density required for the waveguide effect is quite low. For example, the electron density in metal is many orders higher than that necessary to establish the waveguide effect in the microwave region.

For a medium to be capable of affecting the propagation of waves, its characteristic frequencies must be comparable to the excited wave frequencies. This means that the Langmuir (or Larmor) plasma frequency should be of the order of the excited wave frequency,  $\omega_L \sim \omega$ . For microwaves, this condition is satisfied with plasma densities as low as  $10^9$  to  $10^{13}$   $\text{cm}^{-3}$ , where rf energy losses due to Coulomb collisions with plasma particles are small.



Since for low collision frequency  $\nu \ll \omega$ , rf energy losses are proportional to  $\sigma \sim (\omega_L^2/\omega^2)\nu$ , their further reduction can be achieved by heating plasma to 10 to 100 eV because this reduces  $\nu$  as

$$\nu \sim \frac{n_p}{T^{3/2}}$$

For the density range of  $10^9$  to  $10^{13} \text{ cm}^{-3}$ , ionization losses of particles passing through plasma, proportional to plasma density, are negligible:  $dE/dx \sim 10^{-5}$  to  $10^{-6} \text{ eV/cm}$ . This means that plasma is transparent to the accelerated particles. However, the acceleration mechanism tends to bunch the particles, and the reverse coherent acceleration effect may increase these losses considerably. They are still negligible, nevertheless, for currents up to tens of amperes.

Other basic problems with this method are the difficulty of producing stable highly ionized plasma and the possibility of nonlinear effects caused by changes in plasma properties under the action of propagating waves. Proper control of the nonlinear effects, however, can actually improve the efficiency of acceleration.

The mechanism of particle acceleration in plasma depends on the excitation of intense longitudinal oscillations in plasma produced by the injection of electron beams [87]. According to theoretical [88] and experimental [89, 90] investigation of the nonlinear stage of plasma-beam interaction, 30 percent of beam energy is expended on excitation of oscillations, 30 percent on plasma heating, and 15 percent on beam heating. The theory of this interaction, based on the study of various types of instabilities, dates back to the fifties when it was developed primarily in the course of research on controlled thermonuclear reactions (CTR). In this connection, we refer to an early (1961) paper by Faynberg [91] in which he provides a detailed analysis of beam-plasma instability theory. Although it was written from the CTR viewpoint only, its basic concepts are still being used by members of Faynberg's teams whenever they deal with beam-plasma interaction problems. For this reason it is instructive to consider this paper in some detail here despite the fact that most ideas postulated in it are well-known to specialists.

Despite apparent differences in the various types of beam-plasma interactions, they can all be reduced in essence to the Cherenkov effect, anomalous and normal Doppler effects, and plasma polarization effects due to the motion of charged particles. Since plasma density  $n_p$  is in most cases relatively low ( $n_p = 10^{12}$  to  $10^{14}$ ) the energy losses of individual charged particles per length of path due to these effects are negligible and amount to something like  $10^{-3}$  to  $10^{-5}$  eV/cm. However, when the interaction involves large bunches of these particles, the individual losses per particle are much greater due to the collective interaction effect. Thus, the coherent collective interaction of beam particles with plasma result in beam energy loss to plasma than can reach  $10^3$  to  $10^4$  eV/cm per particle in a bunch of  $10^7$  to  $10^8$  particles. Such an interaction appears to be responsible for a number of instabilities in plasma and for the establishment of Maxwellian distribution in the absence of collisions.

According to theory developed by Faynberg, as well as by Bohm and Gross in the United States, beam instability is large if the directed beam velocity exceeds the thermal velocity of plasma electrons. The basic process responsible for this instability is the Cherenkov effect, involving longitudinal plasma waves. If the beam density is much lower than the plasma density, the spectrum of excited high frequency oscillations determined by the Cherenkov effect lies in the frequency range close to the Langmuir frequency. The growth rate of these instabilities is proportional to the cubic root of the beam to plasma density ratio:  $\delta \approx \omega (n_b/n_p)^{1/3}$ .

Research has established about 20 types of instabilities, most of which fall into one of the three large groups corresponding to the three elementary processes that generate the instabilities.

1. *Instabilities due to the Cherenkov effect* in the interaction of electron and ion beams with plasma in a magnetic field. These instabilities occur when the beam velocity equals the phase velocity of plasma waves and causes high-frequency and low-frequency oscillations. Low-frequency oscillations include ion-acoustic oscillations, and Alfvén and magnetoacoustic waves; high-frequency oscillations are longitudinal electron oscillations in magnetic field.

2. *Instabilities due to the anomalous Doppler effect*, which take place when the velocity of the emitting particle exceeds the phase velocity of the plasma wave. In this case, the excited plasma frequency in the frame of reference of the beam coincides with the resonant frequencies of the beam, in particular with the Langmuir or the Larmor frequencies. An important feature of this effect is the fact that the emission is accompanied by transition to a higher energy level. Therefore, it can occur in unexcited oscillators, in particular, in a beam of charged particles moving through plasma in a magnetic field with zero initial transverse energy. The instabilities due to the Doppler effect include the excitation of ion-cyclotron waves and high-frequency electron oscillations at the Larmor frequency.

3. *Instabilities due to the normal Doppler effect*, which are caused by an electron moving in a magnetic field and having an initial transverse energy, and occur when beam velocity is below plasma phase velocity.

These instabilities may occur with a comparatively low electron velocity which decreases the threshold current necessary for the instability to arise. The threshold current in one of the above cases can be even lower than that required for a hydrodynamic instability. However, the threshold current is determined not only by the critical velocity of the directed motion, but also by the density of electrons participating in this motion. Therefore, a number of instabilities that appear at high velocities of directed motion may require lower currents, if the density of participating electrons is low enough. The growth rates of these instabilities are very high. For high-frequency instabilities the growth rate amounts to  $10^{-9}$  sec, and is somewhat lower for low-frequency instabilities.

Using the growth rate, we can compare the energy losses sustained by individual particles and by particles moving in bunches interacting with plasma. As noted above, the losses by particle bunches are much higher due to the coherent interaction effect. All the above instabilities occur in homogeneous plasma where  $\delta n = \delta T = 0$ . The presence of inhomogeneities considerably weakens and disrupts the above types of instabilities, although it can also lead to the occurrence of new types of instabilities.

An instability is called absolute if the initial perturbation increases in time at any fixed point of space. It is called current-convective instability if the initial perturbation, while increasing, drifts out of the system with the beam, so that the instability decreases in time at each point of space. In the case of a current-convective instability, the perturbation has no time to develop to high values within the system. The interaction of two opposed beams generates an absolute instability, while the interaction of two beams moving in the same direction produces current-convective instability. Absolute instability in general exists in those cases where feedback is present. The instability of self-focusing electron-ion beams is convective.

The behavior of instabilities depends to a considerable degree on the geometry of plasmas. The greatest difference is between bounded and unbounded plasmas in the absence of magnetic field: slow transverse waves cannot propagate in unbounded plasma. The effective interaction of free particles with plasma waves and the Cherenkov effect are then impossible. On the other hand, slow waves can propagate in plasma bounded in the radial direction, as well as in plasma bounded in the direction of propagation of waves, especially in a spatially periodic plasma. The elementary processes determining the plasma-beam interaction are a function of the dispersion of the system, that is, the dependence of phase velocity on frequency. We can therefore expect that the transition from unbounded to bounded plasma changes such instability conditions as critical velocity and current of the beam, the frequency spectrum, and the growth rates. Experimental results with bounded beams show that when the plasma wavelength becomes comparable to the beam radius, the instability wavelength increases considerably and at the same time the growth rate decreases to a large extent.

Nonlinear effects are very significant in the region of long wavelengths and low phase velocities.

As the amplitude of the excited waves increases, a number of nonlinear effects appear which tend to decrease the instability. Since the phase velocity of the wave depends on the amplitude, the increasing amplitude disrupts the synchronism between the beam and the wave and

decreases the effectiveness of interaction. This synchronism can also be disrupted by a reduced beam velocity due to energy losses sustained in the excitation of oscillations. The effect of the excited oscillations on the distribution of electrons in the beam, in turn, decreases the number of particles that give up beam energy to the wave and, conversely, increases the number of particles absorbing the wave energy. This equalizes the distribution function and disrupts the instability. Nonlinear effects in the interaction also increase the temperature of the beam and plasma even in the absence of collisions [91].

### C. INSTABILITIES WITHIN THE ELECTRON BEAM

A unique theoretical treatment of the problem of generation, amplification, and frequency conversion of microwaves by the beam-plasma interaction mechanism has been performed by V. A. Buts with direct supervision and support by Faynberg and V. I. Kurilko [92, 93, 94].

The basic principle involved in this work concerns the internal instabilities of the electron beam and the radiative effect of accelerating electrons. Buts appears here to fill the gap left by V. P. Silin, a principal theoretician of Rukhadze's group (see above), in his overall approach to beam-plasma instabilities, where he did not consider the radiation of individual accelerating particles.

Buts postulates a homogeneous unbounded electron beam moving in a medium. If the beam velocity is greater than the velocity of wave propagation in the medium, the beam becomes unstable. However, the exponential growth rate of instability in the beam is possible even if the condition for the Cherenkov effect is not met, provided the medium is inhomogeneous or the beam electrons change velocity.

The instability consists of both longitudinal and transverse electromagnetic waves whose growth rate and frequency are proportional to the acceleration and density of electrons in the beam. The transverse waves propagate at an angle to the beam axis. Unlike the longitudinal waves, the frequency of the transverse waves is little affected by mode-rate beam velocity changes. The development of this instability is shown theoretically to occur even if the ion background is neglected, except for space-charge neutralization.

The physical mechanism of the instabilities within the electron beam is as follows. The radiation of each accelerating electron is neutralized by its neighbors in a homogeneous unperturbed beam. In the presence of a density perturbation, the electrons radiate coherently at a wavelength corresponding to the perturbation wavelength. This, in turn, increases the density perturbation and causes an exponential rise in longitudinal and transverse waves.

The analysis, performed in a hydrodynamic approximation, is valid for wavelengths exceeding the Debye length.

Buts also considers a specific case of an electron beam in a metal waveguide and strong magnetic field. The waveguide is filled with plasma with periodic inhomogeneities. The beam charge is neutralized by ionic background. Under such conditions the growth rate of electromagnetic oscillations depends on the emissive capability of electrons and their density. The intensity of radiation can be increased by increasing the density gradient in the periodic inhomogeneity structure of plasma in the waveguide. The system also permits the generation of transverse waves, thus eliminating the need for an intermediate conversion of the longitudinal beam oscillations into transverse electromagnetic waves, normally expected of plasma amplifiers and oscillators.

#### D. CONTROL OF INSTABILITIES

Instabilities that produce high-frequency (1000 to 6000 MHz) and low-frequency (10 kHz to 30 MHz) plasma oscillations, as well as intense ion currents that can reach values comparable to those of the electron current in the primary beam are the subject of a detailed investigation by Faynberg's group. The principal hypothesis is that ion acceleration and heating is due to the lf oscillations [95].

The lf spectrum can be subdivided into three regions: (1) ion-acoustic oscillations ( $k_z \gg k_1$ ), (2) drift instabilities due to plasma inhomogeneities ( $k_1 \gg k_z$ ), and (3) instabilities due to plasma non-equilibrium ( $k_z \gg k_1$ ) [96]. Control of these instabilities consists mainly in an attempt to concentrate lf oscillations in the ion-acoustic region and to suppress relaxation oscillations generated by the lf.



Relaxation oscillations in plasma-beam interaction occurring in a magnetic field are triggered by fast diffusion of plasma from the region occupied by the electron beam. Plasma diffusion is in turn due to ion-acoustic oscillations. The relaxation cycle proceeds as follows: diffusion reduces plasma in the beam region below a critical value, plasma-beam interaction stops, and the power of hf electron oscillations excited by the beam decreases, as does the power of ion-acoustic oscillations; as a result, plasma diffusion stops, plasma density rises again above the critical value, the beam excites hf electron oscillations which generate ion oscillations, diffusion intensifies, etc. Relaxation oscillations, by introducing relatively long pauses in the plasma-beam interaction process, limit significantly the power transfer from beam to plasma via electron oscillations.

This picture was observed whether the primary electron beam current was of the order of milliamperes or of several amperes [97].

Experiments show [98] that intense lf transverse oscillations (10 to 100 kHz) arise when the hf power reaches a threshold value, causing an intense diffusion and strong amplitude modulation of hf oscillations leading to relaxation oscillations. The diffusion coefficient in this process exceeds Bohm's coefficient. The hf threshold power necessary to excite transverse ion oscillations is practically the relaxation threshold and also the limit of power that can be transferred from beam to plasma. The threshold was shown to be very sensitive to an external potential that can be applied to an electrode placed in the path of the beam in plasma. For a potential of 45 V, the threshold power increases four times in comparison with zero potential. The electrode thus affords the means of controlling the average power of hf oscillations.

The introduction of an external electrode into the plasma-beam interaction region does not alter the interaction behavior when the electrode is at zero potential. However, a positive potential at the electrode disrupts the oscillations, i.e., it alters the boundary conditions for the excitation of lf oscillations through a feedback between the interaction region and the interelectrode gap of the electron beam source. Plasma diffusion due to the ion-acoustic oscillations

causes a large quantity of ions to enter the accelerating field of the source. Since the ion current is subject to lf density modulation, the current modulates the cathode space charge and, consequently, the electron beam, which intensifies the excitation of lf oscillations in the interaction region. Such a feedback is affected by changes in the potential on the collector or on other electrodes introduced into the region. A negative potential naturally increases the feedback and consequently intensifies lf oscillations. A sufficiently large positive potential can fully suppress the feedback. The suppression of ion-acoustic oscillations increases the critical plasma density and thus allows for the control of instabilities in the plasma-beam system. Such a control can thus be achieved by the relatively simple means of an external electrode [97].

Another means of controlling lf oscillations studied by the group is modulation of the electron beam by a relatively weak rf signal. The experimental work was performed with beams whose parameters were of the order of 5 to 10 keV, 0.1 to 4 A, and 100  $\mu$ sec pulse length. The beams created plasma of  $10^{10}$  to  $10^{13}$   $\text{cm}^{-3}$  in a drift tube under 1 m long. The magnetic field was 1 to 2 kgauss. Modulation can be effected with either hf or lf signals.

In the hf case, two frequencies are applied simultaneously [95, 96]. Mixing of the two frequencies results in a difference-frequency modulation. Continuous variation of one of the hf signal frequencies allows one to scan the entire lf spectrum; together, with amplitude variation, the two frequencies can produce the required energy density in any desired region of the lf spectrum. In this manner, by controlling the lf bandwidth and its energy density, one can effectively produce high-energy ions. Direct lf modulation of the electron beam was performed experimentally at 150, 300, 500 kHz (ion-acoustic) with a modulating signal amplitude of 160 V [99].

The experiments show that the modulating signal as weak as 2 W can result in an 80 to 100 percent modulation of a 40 kW beam. Intense 500-kHz oscillations were observed in the resulting ion current recorded by a Faraday cup at the end of the drift tube. The ion current had a power of 6 kW for an input electron beam of 30 kW and 4 A. The

narrowing of the low-frequency spectrum  $\Delta\omega/\omega \sim 1.13$ , and the disruption of drift instabilities are attributed to the electron beam modulation. Thus premodulation of the beam converted at least 20 percent of the initial electron beam energy into acceleration of plasma ions.

Interaction of unmodulated electron beams with plasma excites only high-frequency modes. This process is most efficient when Langmuir waves are excited at the plasma electron frequency. High-frequency modes interact with one another and also with the low-frequency modes that are not directly excited by the electron beam. Deep modulation of the beam introduces low-frequency oscillations into the beam-plasma system. Resonant excitation occurs when the modulation frequency coincides with the natural low frequencies of plasma.

Another possible mechanism of excitation of low frequencies in the plasma-beam system is variation in the high-frequency oscillation growth rate due to the low-frequency modulation of the electron beam density.

The observed 100 percent modulation of the ion current shows that the above method is highly efficient. It transfers energy from the electron beam to plasma producing ion-acoustic oscillations which heat and accelerate ions in the plasma-beam discharge in the course of collective nonlinear interaction between particles and waves.

#### E. GENERATION OF NARROW BANDWIDTH

The investigation of microwave emission from plasma-beam interaction to obtain a sufficiently narrow frequency band (the problem of the monochromatic wave) has been based on computer simulation. The theory of this effect postulates two stages of the interaction process formulated in the early papers [88].

The first -- hydrodynamic -- stage generates a narrow band of frequencies, i.e., the monochromatic wave, whose growth rate is  $\delta \approx \omega_L (n_b/n_p)^{1/3}$ . Here  $n_b/n_p \ll 1$ . The designation of this stage is drawn from analogy to hydrodynamic turbulence in which nonlinear interaction of several perturbations sometimes leads to a preferential growth of a single specified perturbation and a suppression of all the others [100].

The second -- kinetic -- stage follows because energy dispersion of the beam decreases  $\delta$  to  $\omega (n_b/n_p)$ .

Monoenergetic beams ( $k|\Delta v| \ll \delta$ , where  $|\Delta v|$  is thermal energy dispersion in the beam) are in resonance with every harmonic of the instability oscillations, which become very strong. These oscillations, in turn, increase the energy dispersion of the beam if their energy exceeds a certain threshold. However, because the beam ceases to be monoenergetic, the instability growth rate decreases [101].

The energy spread in the initially monoenergetic beam is due to feedback from plasma waves to the beam. Charged beam particles are captured by the potential well of the excited plasma wave, causing oscillation of the plasma wave amplitude and phase dispersion in the captured particles. During the hydrodynamic stage, the wave amplitude increases exponentially; when a considerable portion of beam particles has been captured, marking the onset of the kinetic stage, the average wave amplitude becomes constant and lower than beam energy [102]. The capture of beam electrons creates bunching on the beam. Polarized emission from the bunches results in instabilities, which in turn, produce random modes in plasma emission [103].

The problem here is to extend the hydrodynamic stage during which a monochromatic plasma emission can be obtained. Modulation of the beam with a frequency close to the natural plasma frequency and low amplitude, sufficient only to exceed noise amplitude, is found to increase significantly the length of path over which the excited plasma wave remains monochromatic [104].

While an unmodulated beam excites broadband oscillations with relatively low field intensities of each harmonic, modulation narrows the spectrum and creates phase bunching which, in turn, decreases energy dispersion in the beam, i.e., decreases the effective temperature of the beam and plasma [105].

Another aspect of the instability behavior in the plasma-beam interaction process concerns the relativism of the electron beam. Relativistic, in contrast to nonrelativistic, beams substantially increase the portion of energy that goes to excite oscillations during the hydrodynamic stage, if the instability growth rate is high enough.

These instabilities were analyzed by Dorman [106] in 1962 in terms of a linear theory, but the theory is deemed inadequate by Faynberg [101]. According to Faynberg's quasi-linear theory, relativistic beam energies decrease the instability growth rates somewhat because of the increase of the particle mass. However, the instability energy must be much higher in order to produce a significant dispersion in the beam. This means that the beam remains monoenergetic longer and a larger portion of energy is given up by the beam in the hydrodynamic stage. In the ultrarelativistic case --  $(n_n/n_p)^{1/3} \gamma \gtrsim 1$  -- the instability energy is equal to the beam energy in the hydrodynamic stage. In this case, there is both high instability energy and high instability growth rate. In a strong magnetic field, the fraction of beam energy expended on the excitation of instability oscillations in the hydrodynamic stage increase  $\gamma$  times over the nonrelativistic case. This is due to the low energy dispersion in the beam, which remains monoenergetic even though the momentum dispersion is high. As noted above, the relativistic increase of mass tends to weaken the feedback effect of the excited field in plasma on beam motion, decreasing the instability growth rate. One way to counteract this weakening is to enhance the intensity of the collective interaction mechanism [107].

The effectiveness of excitation of collective oscillations by a charged particle beam depends on three factors: emission intensity in each elementary act; coherence of the elementary emitters; and bunching of the emitters by the excited field. The interaction intensity could be enhanced considerably if bunching, caused by external or by collective fields, could ensure a high degree of coherence of spontaneous emission within each bunch and among the bunches. This could eliminate the need of beam self-modulation by the emission field and also reverse the undesirable effect of feedback weakening which, in this case, would actually increase the maximum amplitude of the excited field.

Experiments performed to verify this hypothesis were based on the principle that the "modulation" frequency  $\omega_M$  (number of bunches per second) should be close to plasma Langmuir frequency ( $\omega_M \approx \omega_L$ ) and that the electron beam current should be above a certain value (in this case, 1 A).

A linear accelerator with iris-loaded waveguide, described in [108, 109], delivered a 2-MeV, 1-A, 2- $\mu$ sec beam, 10 mm in diameter, with 2805-MHz modulation frequency in a magnetic field of 2000 Oe. It is interesting to note that the machine was built in 1963 as a 5- to 40-MeV linear electron accelerator producing 80-mA, 1.5- $\mu$ sec pulses at 50 pps. It was considered at that time the most advanced of the medium-energy linear accelerators built at the Physicotechnical Institute. For the experiments discussed here, performed in 1972, the accelerator must have undergone some modifications.

In the present experiments, beam energy spectra were measured as functions of plasma density. The plasma density of  $10^{11} \text{ cm}^{-3}$  has a Langmuir frequency corresponding to the bunching frequency used in the experiments. Beam energy loss was indeed found to be in resonance with plasma density, with the loss maximum determined at the density of  $10^{11} \text{ cm}^{-3}$  and amounting to 10 percent of the initial beam energy. On both sides of the optimum, the energy losses of beam electrons significantly decreased and vanished altogether with  $n_p \lesssim 10^{10} \text{ cm}^{-3}$  and  $n_p \gtrsim 5 \times 10^{12} \text{ cm}^{-3}$ .

Energy losses in the beam also depend on beam current. Decrease of beam current to one-half of its value significantly reduced its losses even at the optimum plasma density. This explains the negative result obtained by Mendell and Holt [110], who neither ensured coherence between plasma and beam by failing to make  $\omega_L = \omega_M$ , nor used sufficient current.

Measurement of the microwave field ( $E_z$ ) due to the collective interaction mechanism showed the effectiveness of the mechanism: The spectrum peak coincided with the beam modulation frequency of 2805 MHz. The half-width of the spectrum  $\Delta f \simeq 10$  to 12 MHz was not more than 1.5 times greater than the half-width of 8 MHz that the beam shows without interaction with plasma.

The above results were obtained for the case of a decaying plasma when the plasma density decreased over a distance of 1 m from the entrance to the waveguide to its exit. A decrease in density gradient by a factor of 2.5 increased losses up to 300 to 350 keV [107, 111].

The results are reported as proof that collective coherent interaction between a modulated beam of relativistic electron and plasma



has been obtained. The coincidence of the phase velocity of the excited wave with beam velocity proves that the interaction is based on the Cherenkov effect. The relatively large losses of beam energy indicate the collective nature of this interaction. The theoretical value of energy loss for a single electron is 10 keV, which is an order lower than the measured value of 200 keV. These experimental losses can be attributed only to the increase of the excited fields of the electron bunches successively entering the plasma. The coherence is also indicated by the linear rise of field amplitude and beam energy losses.

The experimental and theoretical considerations showed that:

1. The relative energy losses of a low-current beam (1 A) are comparable to the losses of high-current unmodulated relativistic beams, thanks to modulation and coherence. It is hoped that further decrease of plasma inhomogeneity will increase these losses.
2. Relativistic modulated beams can excite narrow-band oscillations in long (2 m) waveguides. The excited electric fields are concentrated mainly within the waveguide.

Thus, while the relativistic increase of electron mass was shown to have weakened the field-to-beam feedback, the resonance nature of the interaction delayed the hydrodynamic stage, strongly increasing the energy transfer from the monoenergetic beam to plasma.

The theoretical considerations described above were developed on the basis of early experiments and computer simulation involving relatively weak electron beams of a fraction of an ampere. The modulation methods producing small longitudinal energy spreads entail other problems when applied to high-current beams.

At high beam energies, the length of the interaction path, necessary for instability growth, increases; with short lengths modulated beams are required. This is difficult to do for high-current relativistic beams, and self-modulation is preferred. Self-modulation occurs in the interaction of the beam with a periodic structure whose resonance frequency is close to Langmuir plasma frequency.

Subsequent experiments were performed with a much stronger beam and an iris-loaded waveguide as the slow-wave structure. The accelerator features were as follows [112]:

- o Electron beam -- 1 MeV, 60 kA, 30 nsec, energy dispersion 20 percent.
- o Accelerator -- Marx generator, Blumlein transmission line with distilled water, needle cathode.
- o Drift tube -- 3 m long, filled with nitrogen; the beam was magnetically and electrostatically neutralized.

Self-modulation was achieved with an iris-loaded waveguide 1 m long, designed for 2500 to 2800 MHz. At gas pressures of 0.1 to 1 mm Hg, the beam produced plasma with a density of  $10^{12}$  to  $10^{13}$   $\text{cm}^{-3}$ . The interaction path length with positive growth rate of the oscillation was 20 to 30 cm. The self-modulation of the beam produced a  $10^7$ -W microwave burst, 20-nsec long, with a peak at 2600 MHz. These results were reported in 1972.

In 1967 Faynberg wrote [86] about experimental yields of plasma oscillation intensities of the order of 200 kW achieved with electron beams under 1 MeV. He also noted at that time the ongoing experiments with the excitation of microwave plasma oscillations by 10-MeV beams and planned experiments with 100-MeV beams. Subsequent publications of his group have so far failed to report on the 100-MeV work; if the above experimental report is an indication, such beam energies, especially in conjunction with kA current, have not yet been performed.

#### F. LINEAR PLASMA BETATRON

The linear plasma betatron proposed by Faynberg in 1961 [91], combines the properties of a linear induction accelerator and a cyclic plasma betatron. However, the electron beam is accelerated in plasma, significantly increasing the current, and the electrons transverse the system only once, avoiding some types of instabilities [113].

The linear plasma betatron consists of 12 single-turn electromagnets spaced along 60 cm of a glass tube 1 m long and 4 cm in diameter.

The thyatron power supply delivers 25 kV at 5 pps. A 20 MHz, 0.5 kW oscillator ionizes argon or hydrogen at  $10^{-1}$  to  $10^{-3}$  mm Hg to initial plasma density not exceeding  $10^{10}$   $\text{cm}^{-3}$ . After gap breakdown plasma density rises to  $10^{13}$   $\text{cm}^{-3}$ . Total discharge current ranges from 10 to 5000 A. The accelerating voltage is 40 kV. A diagram of the accelerator is shown in Fig. 11.

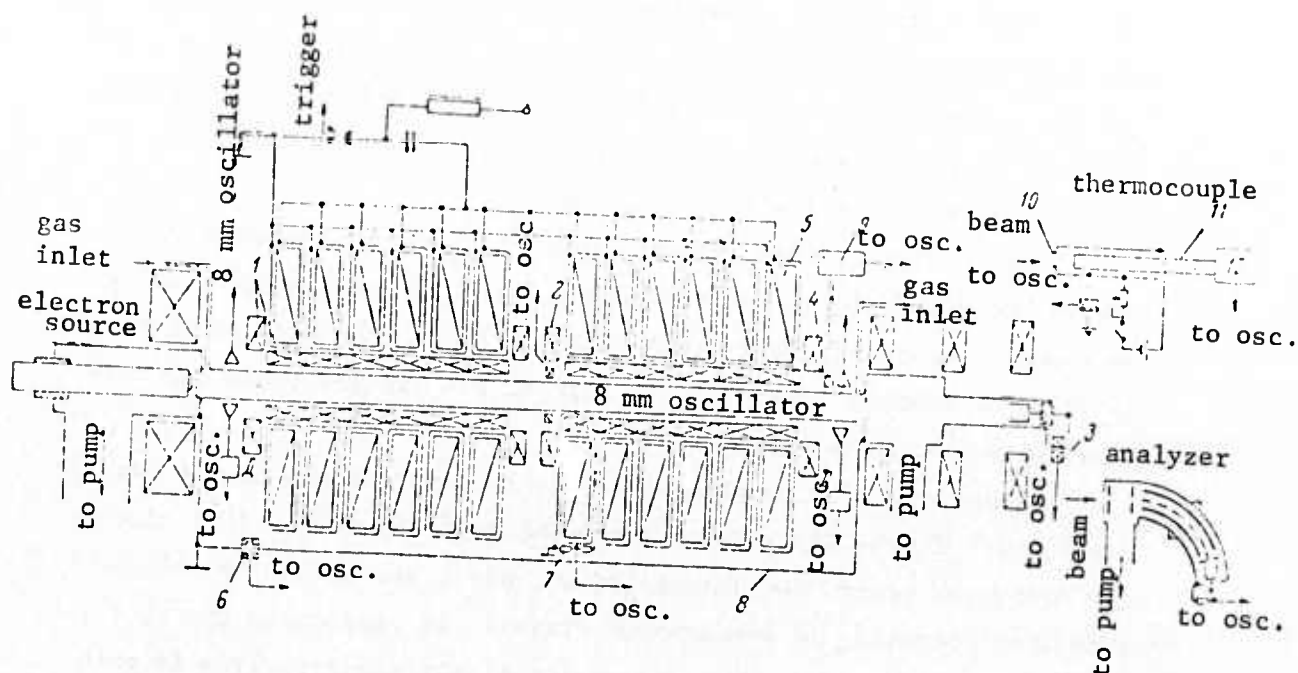


Fig. 11 -- Linear plasma betatron [114]

- |                          |                        |
|--------------------------|------------------------|
| 1 - magnetic field coils | 7 - voltage divider    |
| 2 - diamagnetic probe    | 8 - flange straps      |
| 3 - Rogowski ring        | 9 - wavemeter          |
| 4 - loop antenna         | 10 - platinum target   |
| 5 - inductors            | 11 - optical waveguide |
| 6 - Rogowski ring        | 12 - photo-multiplier  |

The critical field required for the acceleration is:

$$E_{cr} = 4.5 \times 10^{-8} \frac{n_2}{T_e}$$

where  $n_2$  is plasma density. For  $n_p = 10^{12}$   $\text{cm}^{-3}$  and  $T_e = 10^4$ ,  $E_{cr}$  is of the order of a few V/cm [113].

In high-current experiments, the accelerator is used with an external electron source to generate initial plasma, delivering a 6-A, 10-kV, 160- $\mu$ sec beam 2 cm in diameter.

The goal is the acceleration of plasma electrons by external electric field to produce intense electron beams. The problem is created by instabilities (ion-acoustic, hose, and Buneman types) which prevent the acceleration. The linear plasma betatron may solve the problem. In the betatron some instabilities, such as the ion-acoustic type, do not arise. Drift instabilities, such as hose and Buneman types, tend to be carried out of a finite-length system by the beam of accelerated electrons before they reach an intensity level capable of dissipating the beam.

Given a limited cold-cathode emission, the voltage applied to plasma becomes redistributed, creating very high accelerated fields in a small region adjacent to the cathode. The result is an intense electron beam whose energy equals that of the applied field and current is in the range of kA.

Another method of weakening instabilities consists in the use of plasma with decreasing density along the beam (Ryutov). This alters the mechanism generating instabilities, which becomes quite different from that operating in homogeneous plasma. In particular the intensity of rf fields that cause velocity spread in the electron beam is much lower in inhomogeneous plasma; also, the plasma density gradient prevents electrons from acquiring velocities in excess of the applied field.

Experiments were performed to determine the velocity distribution of beam electrons [113], to investigate drift instabilities that disrupt the beam in cyclic accelerators [114], and to compare instability behavior in plasma with and without axial density gradient [115].

In the latter experiment, plasma ionized by the primary beam had a density of  $10^{13}$  cm $^{-3}$  for an initial pressure of  $5 \times 10^{-5}$  mm Hg. About two-thirds of the current in the betatron was in the beam entering the acceleration tube. The beam of accelerated electrons had 800 to 1000 A per pulse and the same energy as the field applied to the plasma (50 kV). Instabilities developed only for voltages below 10 kV.

When the initial pressure in the accelerating tube was dropped to  $10^{-5}$  mm Hg the beam created an inhomogeneous plasma whose density decreased from  $10^{13}$   $\text{cm}^{-3}$  at the beam entry window to  $10^{11}$   $\text{cm}^{-3}$  at the opposite end. The application of an electric field of 60 kV to this plasma also produced an intense beam of electrons, almost all of which left the accelerating tube. The beam energy was the same as that of the applied field, although the beam was more monoenergetic than in homogeneous plasma.

Beam-plasma interaction producing rf and optical emission was observed here as in the case of homogeneous plasma, although it was an order of magnitude lower.

The results show that the cold-cathode emission of electrons was limited, as indicated by the strong dependence of beam current on cathode material and plasma density. The limited emission redistributes the applied voltage so that it falls in a narrow region at the cathode creating electric fields in excess of 30 kV/cm. Fields of this magnitude generate in the near-cathode region an intense beam of electrons whose energy equals the applied voltage. The density of the beam is  $10^{11}$   $\text{cm}^{-3}$  amounting to 0.1 percent of plasma electron density near the cathode.

Under the above experimental conditions, the ion-acoustic instability occurs theoretically for fields below 350 V/cm, which is much below the near-cathode field intensity of 30 kV/cm. Thus, it is concluded that ion-acoustic instability cannot develop in the near-cathode region.

Buneman instability requires that beam and plasma density be approximately equal. Since the density of fast particles in this experiment is lower than plasma density, Buneman instability also does not arise.

The given experimental conditions are most conducive to the development of beam instability. Since  $n_b/n_p \sim 10^{-2}$  and the velocity of fast electrons moving through plasma  $v_e \gg v_{Te}$ , the frequency of rf oscillations excited by this instability is determined by the Cherenkov emission condition  $\omega = kv_0$ . Oscillations at plasma frequencies were observed and could be attributed to beam instability.



The instability growth rate is  $\delta_0 \sim \omega_L (n_b/n_p)^{1/3}$  for a mono-energetic beam and  $\delta = [(n_b/n_p)^{1/3} (v/\Delta v)]^2 \delta_0$  for a beam with velocity spread of  $\Delta v/v \gg (n_b/n_p)^{1/3}$ . Substituting experimental values into these expressions we obtain  $\delta_0 = 10^{10}$  and  $\delta = 5 \times 10^8$ . The observed value for  $\delta$  was  $10^8$ , which indicates a beam with a velocity spread.

In homogeneous plasma, the beam of accelerated electrons lost roughly one-third of its electrons to scattering by plasma oscillations, whereas in plasma with a density gradient, the beam left the accelerating tube almost intact. The rf emission level in a gradient plasma was an order lower than that in homogeneous plasma, and X-ray emission was extinct. Finally, in gradient plasma there were no electrons faster than the applied voltage, and the energy spectrum itself was much narrower. All this means that plasma with a density gradient along the direction of the beam considerably weakens beam instability.

The beam current emerging from the accelerating tube reaches 1 kA with an energy of 40 keV. It is expected that much higher beam powers can be obtained by increasing betatron power. Plasma density gradient sharply decreases beam-plasma interaction and beam loss and narrows the electron energy spectrum.

#### G. THE ELECTRON BEAM AS A LASER PUMP

The use of electron beams in laser systems has been common for some time in many laboratories. In the Soviet Union, laser researchers, such as N. G. Basov of the Lebedev Physics Institute, use electron beams to excite the active medium by electron-atom collisions, or to preionize the active medium. The particle beam specialist of the same institute, M. S. Rabinovich, has developed a fast-pinch discharge laser to increase the emission power. A more unique approach toward the same end was made by Faynberg, who applied his theory of collective effects in beam-plasma interaction to a new laser pumping principle.

Faynberg was concerned with increasing the pumping effectiveness and extending the frequency range of lasers, especially in the short-wave region of the optical spectrum. According to his findings,



collective interaction pumping makes it possible to produce stimulated emission on a wide range of frequencies and also in a variety of gaseous media [116].

Conventional gas-discharge lasers operate at a relatively high pressure ( $10^{-1}$  to 10 mm Hg) and a low electron temperature of 5 to 6 eV. The fast-pinch discharge laser of Rabinovich reaches 20 eV and therefore significantly increases emission power [117]. Further increase in the efficiency of excitation of ionic lines requires a substantial increase in electron temperature up to the maximum of the excitation function, i.e., the temperature should be about 50 to 100 eV. Coherent emission in the ultraviolet further requires a low gas pressure, as well as a high electron temperature. Both requirements can be met in the beam-plasma discharge in which for a low pressure the electron temperature reaches tens and hundreds of eV. The latter effect can be used to broaden the emission frequency range. Moreover, the discharge produces a relatively large volume of plasma with a high electron and ion density. While the lasing lines could be excited directly by a monoenergetic electron beam, the excitation by plasma electrons is much more effective, since the beam density is generally much lower than plasma density. In this process, absorption is minimized by the Doppler effect due to the intensive motion of ions whose temperature and velocity vary considerably. These features of the beam-plasma discharge make its application to new gas lasers very attractive.

The mechanism of beam-plasma discharge is based on the beam-plasma instability theory developed by Faynberg in the fifties (see Section IV, B, above). The mechanism is briefly summarized as follows: As an electron beam passes through neutral gas, collisions between beam electrons and gas atoms create plasma whose density is comparable to beam density. Collective interaction excites oscillations at the cyclotron frequency  $\Omega$ , if it is lower than Langmuir frequency  $\omega_L$ . The electric field of these oscillations gives up energy to plasma electrons, which further ionize the plasma. Its density increases rapidly,  $\omega_L$  rises above  $\Omega$ , and intense oscillations occur at  $\omega_L$ , due to the Cherenkov effect, and at  $\omega = k_z v$ , due to the normal and abnormal Doppler effects.

The feedback from the excited oscillations to beam electrons spreads their frequencies and phase velocities and randomizes the oscillations themselves. The electric field of the stochastic oscillations produce an intense heating of plasma electrons and ions.

The plasma-to-beam density ratio ( $n_p/n_b \approx 10^3$  to  $10^4$ ) and plasma electron energy, which corresponds to the peak values of the inversion cross-section, readily facilitate high pumping intensities. Furthermore, hf oscillations excited in the course of hf decay cause diffusion and heating of ions, thereby increasing plasma volume. The distribution function departs sharply from the Maxwellian, and peak temperature and density depend only on the reciprocal of the instability growth rate, which reaches  $10^{-10}$  to  $10^{-11}$  sec.

The emission spectrum can be modulated up to  $10^{10}$  to  $10^{11}$  Hz with external rf sources modulating the beam [116, 117, 118].

The first experimental verification of laser action due to the collective interaction mechanism was reported in 1967 [117]. The parameters of the electron beam used in this experiment were 10 to 45 keV, 10 to 30 A, and 40  $\mu$ sec, with a pulse repetition frequency of 1 to 50 Hz. The active medium was argon. The discharge resulted in an electron temperature of 90 eV, plasma electron density of  $10^{12}$  cm $^{-3}$ , and ion temperature of 1 eV. Stimulated emission was observed at 4545, 4579, 4609, 4658, 4880, 4965, 5017, and 5145 Å. Divergence did not exceed 40". The optimum magnetic field at the axis of the discharge tube was 1.5 kOe. At 4880 Å, the emission pulse was 30  $\mu$ sec long, and had a power of 100 W. The experimental setup used is shown in Fig. 12.

The verification of the hypothesis that laser action is due to the collective process is based on the observed coincidence between the peak intensity of coherent radiation and the peak of hf oscillations generated in the course of collective beam-plasma interaction, as well as the maximum electron and ion temperatures. This correlation is attributed to the development of instabilities which generate electric fields, which in turn, increase the electron and ion temperatures.

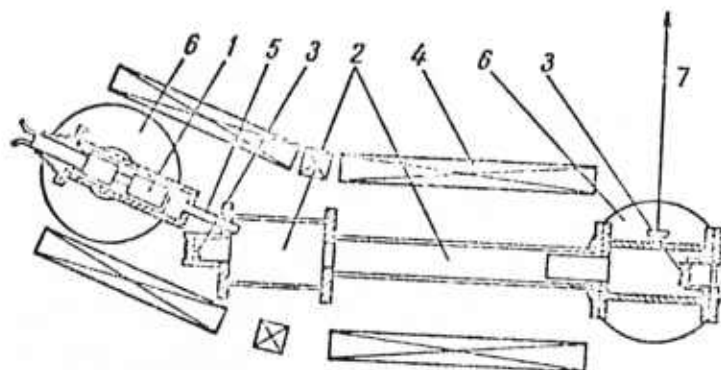


Fig. 12 -- Laser action experiment [117]

- |                  |                                |
|------------------|--------------------------------|
| 1 - electron gun | 4 - solenoid                   |
| 2 - plasma tube  | 5 - pressure differential tube |
| 3 - mirror       | 6 - diffusion pumps            |
| 7 - gas supply   |                                |

The subsequent experiments reported on five years later used a similar electron beam: 40 keV, 35 A, 90  $\mu$ sec [116]. This time a number of gases were employed as active media, including argon, krypton, xenon, nitrogen, and chlorine. The laser tube was 3 m long and 10 mm in diameter. The electron beam offset angle with the tube axis was reduced from  $15^\circ$  in the 1967 experiment to  $8^\circ$ . The magnetic shield was added to protect the mirrors from ion bombardment. Table 5 shows stimulated emission lines obtained in relation to the gas and transition used.

Two types of coherent emission were observed: the pulse type occurring in the pressure range of  $3 \times 10^{-4}$  to  $9 \times 10^{-4}$  torr characterized by a short laser pulse relative to the beam pulse, and the quasi-stationary type above  $9 \times 10^{-4}$  torr. The pressure range of the pulse type also marks a vigorous development of collective processes and of beam instability accompanied by a strong hf and bremsstrahlung X-ray radiation. As before, the stimulated emission power of the pulse type was 100 W for argon.

Faynberg concluded at that point that the application of collective interaction processes to laser pumping significantly widens the frequency range and power of stimulated emission and that the beam-plasma discharge is the most suitable method of pumping lasers in the shortwave region of the optical range.

Table 5 [117]

STIMULATED EMISSION LINES IN RELATION TO  
GAS SPECIES AND TRANSITION LEVELS

Wavelength, Å	Ion	Transition
4764.83	ArII	$4p^2P_{3/2}^0 - 4s^2P_{1/2}$
4879.90	ArII	$4p^2D_{5/2}^0 - 4s^2P_{3/2}$
5145.34	ArII	$4p^2D_{5/2}^0 - 4s^4P_{3/2}$
4765.74	KrII	$5p^4D_{5/2}^0 - 5s^4P_{3/2}$
5681.89	KrII	$5p^4D_{5/2}^0 - 5s^2P_{3/2}$
5419.15	XeII	$6p^4D_{5/2}^0 - 6s^4P_{3/2}$
4896.86	ClII	$(^2D^0)4p^3F_4 - (^2D^0)4s^3D_3^0$
5217.92	ClIII	$4p^3P_2 - 4s^3S_1^0$
5392.16	ClIII	$(^2D^0)4p^4F_3 - (^2D^0)4s^1D_2^0$
5679.59	NII	$(^2P^0)3p^3D_3 - (^2P^0)3s^3P_2^0$

It is of interest to note that, although the above experiments were performed with megawatt beam pulses, Faynberg underscored at the time "the present availability of electron beams with  $10^{12}$  W per pulse." It is this availability and the intensive development of such beams, Faynberg wrote [116], that make the beam-plasma discharge so attractive as a laser pump.

Experiments by the Faynberg group employing  $10^{12}$ -W beams have not been reported so far. The most recent experimental work, published in 1973 [118], does represent some progress in this area. A 0.7-MeV, 30-kA, 30-nsec beam produced by an accelerator consisting of a Marx generator, water-filled Blumlein transmission line, and a field-emission diode with a needle or protrusion cathode, was used.

The beam current density in the experiment was  $6 \text{ kA/cm}^2$ . The laser discharge tube was stainless steel, 270 cm long and 14 cm in diameter. The reported results were obtained without mirrors.  $N_2$  was used because of the relatively long upper level lifetime (40 nsec) and high gain of the  $C^3\Pi_u - B^3\Pi_g$  transition. The pressure was  $10^{-1}$  to 3 torr.

Superradiance was observed at 3195 Å, 3371 Å, and 3577 Å. A sharp peak was observed at 3371 Å, 1 torr. Divergence did not exceed 2°. The emitted laser power at all three lines was  $10^5$  W for 15 nsec.

The evidence that laser action was due to the collective process was based on a comparison of the lifetime of the excited level of  $10^{-8}$  to  $10^{-9}$  sec, with an instability growth rate of  $10^{10}$  sec $^{-1}$  calculated for the given experimental conditions from Faynberg's theory [101].

The alternative process, due to beam electron collisions with gas molecules, is discounted because the density of the inverted state produced by such a mechanism does not exceed  $10^9$  cm $^{-3}$ , which is insufficient for reliable observation of superradiance [118].

## V. THE PLYUTTO GROUP

### A. INTRODUCTION

The research group headed by A. A. Plyutto at the Sukhumi Physico-technical Institute (Georgian SSR), is the smallest and their range of interest the narrowest of the major groups. Nevertheless, the originality of their work, particularly in the experimental area, and their results deserve attention. Yonas wrote that they accomplished what was probably the first successful demonstration of collective acceleration [119]. The group is essentially concerned with the production of intense beams of charged particles in plasma-filled diodes.

The leadership of the group is as follows:

#### *Guidance and Support*

A. A. Plyutto

#### *Review*

A. A. Plyutto

I. F. Kvartskhava

L. P. Skripal'

#### *Consultation*

Ye. K. Zavoyskiy

G. I. Budker

Ya. B. Faynberg

R. Z. Sagdeyev

V. P. Sarantsev

R. A. Demikhanov

Yu. V. Kursanov

#### *Senior Authors*

A. A. Plyutto

K. V. Suladze

G. P. Mkheidze

S. M. Temchin

P. Ye. Belensov

V. N. Ryzhkov

### B. THE ACCELERATING SYSTEM

Plyutto's work on the production of high-current electron and ion beams has been going on continuously since the fifties. Performing experiments with ion beams from spark plasmas at that time, Plyutto



discovered the existence of particles whose energy exceeded the accelerating voltage. Detailed study of these particles led to the production of intense electron beams with a current density of  $10^4$  A/cm<sup>2</sup>, which could in turn accelerate protons to maximum energies of 4 to 5 MeV and carbon ions to 10 to 20 MeV for an average input electron energy of 200 to 300 keV [120, 121, 122]. In the accelerating energy range of 10 to 200 keV, he observed that ion energy increased linearly with the electron energy, leading him to believe that 10- to 100-MeV proton accelerators could be built using 1- to 2-MeV relativistic electron beams [123].

The phenomena involved in the acceleration can be described as follows: A discharge gap of length  $l$  is formed of a plasma source serving as the cathode, and an anode with an external diameter  $D$  and an internal aperture  $d$  leading to a drift tube with a Faraday cup. An accelerating voltage is applied to the plasma-filled gap with a delay of 1 to 2  $\mu$ sec. An electron beam forms and passes through plasma and the anode aperture. When the total current  $I_0$  through the circuit is below a critical value, the beam current falling on the Faraday cup slowly increases with  $I_0$  as  $I = I_0(d/D)^2$ . As the critical current is reached, the gap resistance suddenly increases, cutting off the total current and sharply increasing gap voltage beyond the initial accelerating voltage. At the same time, there is a large jump in the beam current, nearly half of which passes through the anode aperture. This beam, in turn, accelerates ions to energies much higher than the accelerating electron energy [124, 125].

The basic tool in the study of these phenomena is the vacuum-spark plasma source which Plyutto developed in 1954 [126] and has used without major modifications ever since [26, 123].

Vacuum spark is a type of discharge capable of generating dense plasma ( $10^{15}$  to  $10^{16}$  cm<sup>-3</sup>) with a high electron temperature ( $2 \times 10^5$  °K), i.e., with a high electron energy density. The plasma of a vacuum spark is an effective emitter of charged particles whose current density can theoretically reach  $10^2$  A/cm<sup>2</sup> for ions and  $10^3$  A/cm<sup>2</sup> for electrons [127].

The plasma source can be used in the accelerating scheme in one of two ways: Plasma may be injected into an accelerating gap in which

the electric field has already been established, or the gap may first be filled with plasma and the field applied afterward. The first method is called the *plasma-field* and the second, the *plasma-current* regime. The distinguishing characteristic of the latter is that, in the initial stage, the gap is shorted by plasma and thus has a low potential drop. The energy of ions accelerated in the plasma-field regime exceeds the electron accelerating voltage by a factor of 25 to 30 for a nonrelativistic electron beam. While this factor is only slightly higher (35) in the plasma-current regime, the latter yields four times as many protons as the plasma-field regime and produces an intense beam of accelerated carbon ions that is absent in the plasma-field regime [128]. Most of the experimental work in the ion accelerator performed by Plyutto involved the plasma-current regime.

In some experiments, Plyutto used multiple-needle field-emission cathodes instead of the vacuum-spark source, noting the similarities between the vacuum breakdown and formation of electron beams from plasma emitters [129].

The major aim of Plyutto's research has been the production of intense beams of  $H^+$  and  $D^+$  ions. Pursuing this aim, he has developed a comprehensive program of experimental investigation and attempted to construct a theoretical model of the acceleration mechanism. Plyutto's key experiments and equipment are described below.

### C. EXPERIMENTAL WORK

Plyutto developed two models of the plasma source: one with one discharge gap and one with six. Figure 13 is a diagram of their construction.

The spark discharge develops between electrodes 1 and 2 spaced 5 to 6 mm apart. The ceramic tube 4 compresses the discharge mechanically, limits plasma diffusion, and facilitates vacuum breakdown along the tube wall. Electrode 2, with a 4-mm aperture, is made of W or Ta, while electrode 1 is made of Cu and has a channel 3 holding the working medium. Plexiglas was used as the working medium to obtain  $H^+$  ions, and LiD was used for  $D^+$  ions. The working medium can also be spread along the tube wall. Plasma of the vaporized working

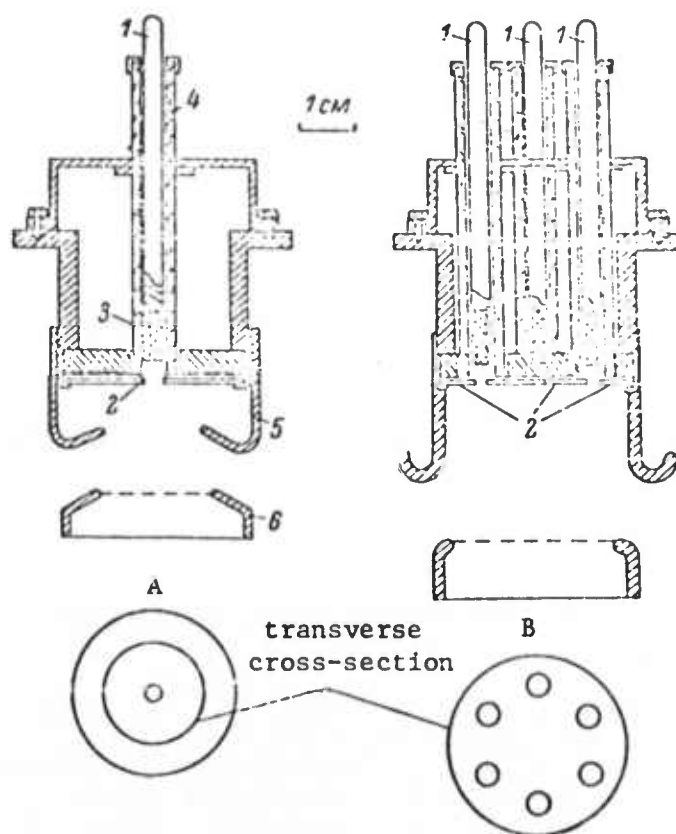


Fig. 13 -- Vacuum-spark plasma source [127]

A - single-gap plug

B - six-gap plug

1,2,5, and 6 - electrodes

3 - channel with working medium

4 - ceramic tube

medium enters the vacuum gap through the aperture in electrode 2 and forms the developed emission surface. The area of active emission is 5 to 7 cm<sup>2</sup>. Electrode 5 preforms the beam and prevents breakdown in the extraction system. The accelerating voltage is applied across electrodes 5 and 6. The aperture in electrode 6 is 35 mm in diameter and is covered with a steel mesh. \*Synchronized operation of the spark channels in the six-gap model results in higher amplitude of ion current and lower amplitude dispersion from pulse to pulse. The operating life of a spark channel is 10<sup>5</sup> to 10<sup>6</sup> pulses.

The plasma source is driven by a 10- to 50-kV Marx generator. The mounting of the plasma source in the accelerator scheme is shown in Fig. 14.

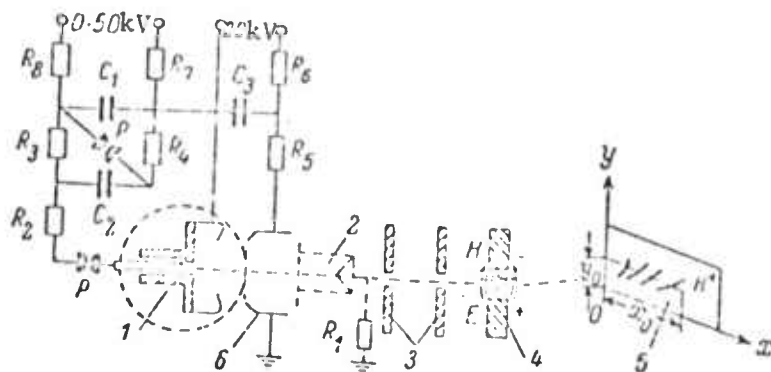


Fig. 14 -- Accelerator system [127]

- 1 - plug
- 2 - Faraday cup
- 3 - collimator
- 4 - magnetoelectric separator
- 5 - photographic plate
- 6 - electrode

A more extensive investigation of this system (see Fig. 15) included an alternating accelerating voltage (1 to 2 MHz), as well as a higher unipolar voltage of 100 kV applied to the gap. The vacuum spark plasma source with the associated accelerator system was tested in 1964-1965 for its capability to produce high-density collimated ion and electron beams [26, 127].

In tests with  $H^+$  ion beams, with Plexiglas inserted in the spark channel, maximum total ion currents of 100 A were observed for a spark discharge current of 3 kA in a 1  $\mu$ sec pulse and 20 kV across the gap. For  $D^+$  ions, with LiD in the spark channel, the maximum total ion current was 50 A for a spark discharge current of 5 kA. The ion current density was within the range of 5 to 15 A/cm<sup>2</sup> and about 40 percent of the ion current in the gap reached the Faraday cup 1 cm behind the anode.

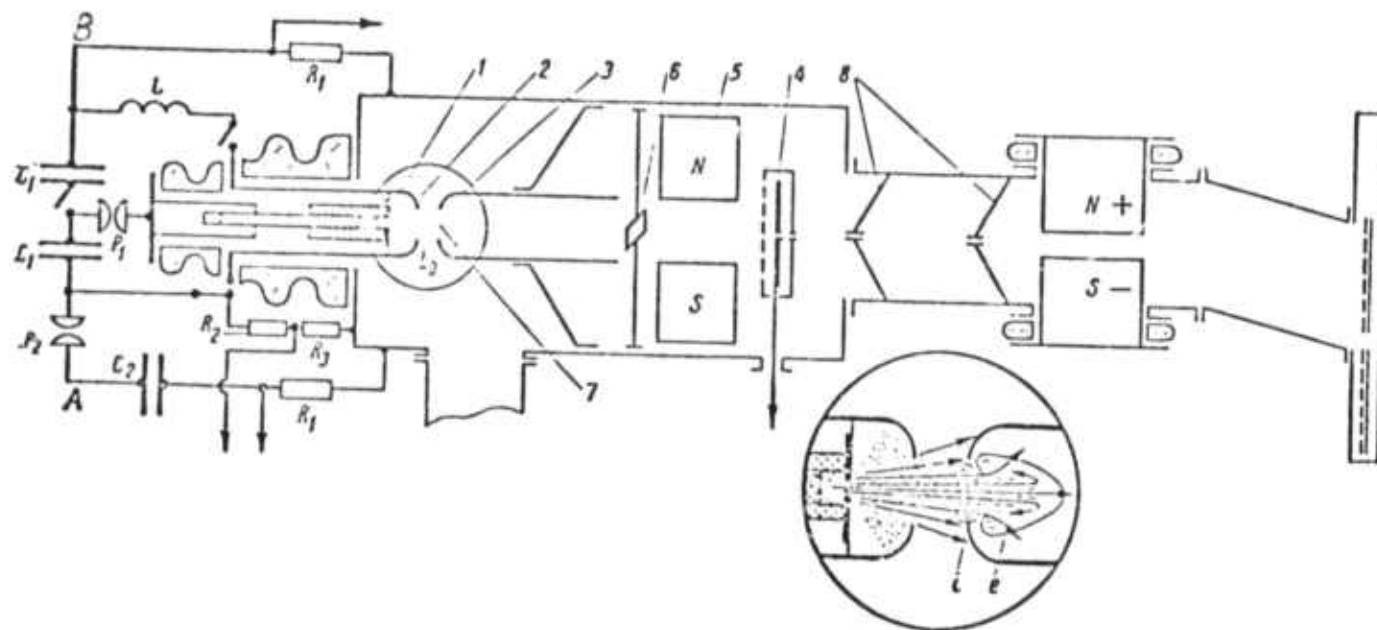


Fig. 15 -- Ion-electron accelerating system [120]

- 1 - capacitor bank
- 2 - spark-source electrode diaphragm
- 3 - accelerating anode
- 4 - collector
- 5 - electron-beam deflection magnet
- 6 - beam aperture
- 7 - electrode aperture
- 8 - collimating diaphragm of mass spectroscopy
- A - unipolar voltage
- B - a-c voltage
- $\ell$  - accelerating gap

It was noted at the time that proximity of the emissive plasma surface to the cathode tended to increase current density. This suggested the possibility of reaching densities of 50 to 100 A/cm<sup>2</sup>, if the surface was close enough.

In the experiments with electron beams employing the six-gap source, electron beam currents of 1000 A were observed for spark-discharge currents of 4 kA and accelerating voltage of 20 kV. The current density was 100 to 250 A/cm<sup>2</sup>.

Spark source 1 (Fig. 15) was driven by a 20- to 50-kV,  $5 \times 10^3$  to  $5 \times 10^4$  nf capacitor bank, producing a maximum current of 1 to 10 kA. The accelerating gap  $l_0$  consisted of spark-source electrode diaphragm 2 and accelerating electrode (anode) 3 with external diameter  $D$  and aperture diameter  $d$ . A unipolar voltage of 0 to 100 kV (A) or 1 to 2 MHz a-c voltage (B) was applied to 3.

Measurement equipment consisted of 6- and 25- $\mu$ m Al foils passing 500 keV and 1.5 MeV protons, collector 4 set 30 cm from the source to determine the quantity of ions per pulse, electron-beam deflection magnet 5, and 2.2-cm<sup>2</sup> beam aperture 6. A  $T_1$ ,  $D_{1,2}$  target set 15 and 30 cm from the source was used to measure the average total number of accelerated deuterons per pulse based on the D-D reaction.

In this experiment the electron beam reached a current density of  $10^3$  A/cm<sup>2</sup>. A linear relationship was observed between the maximum proton energy and the accelerating voltage, with the proton reaching 2.5 MeV for 100-kV acceleration. The number of accelerated ions per pulse was  $4 \times 10^{11}$  protons and  $3 \times 10^{11}$  deuterons.

The acceleration of ions in the electron beam occurred in what was essentially an unstable beam current characterized by steep rises ( $10^{-7}$  sec) and steeper drops ( $10^{-8}$  sec), or current breaks, observed when the spark-discharge current exceeded 100 A. Plasma ions were captured and accelerated by the electron beam in each pulse, at the stage when the beam current reached a peak and was cut off. The accelerating process, in Plyutto's interpretation, is not caused merely by potential difference, because the electron beam and the accelerated positive ions move in the same direction and ion energy is independent of ion charge. Since ion energies exceed 10 to 100 times the external potential difference and the internal accelerating field intensities reach  $10^5$  to  $10^6$  V/cm, the acceleration of ions must be attributed to strong collective interactions of the electron beam with plasma ions [120].

The same experimental setup as shown in Fig. 15 was used to determine the mechanism of acceleration of the primary electron beams in plasma gaps [125]. In the initial stage the beam current  $I$  through aperture  $d$  rose slowly, following total current  $I_0$  according to the relation  $I = I_0(d/D)^2$ . For  $d = 1$  mm,  $D = 40$  mm, and  $I_0 = 2$  kA, and



$I = 1.25$  A. This value was also measured experimentally, indicating the absence of instabilities. Further increase of  $I_0$  beyond a critical value produced a cutoff in the total current accompanied by a rise in  $I$  to 45 A, which amounted to a beam current density of  $5700$  A/cm<sup>2</sup>. The beam current formed in the course of the cutoff of the total current was highly sensitive to the change in a number of circuit parameters. Thus, by increasing the accelerating voltage,  $V$ , to 42 kV, the gap diameter to 12 mm, and the capacitance to  $5.4 \times 10^{-8}$  f, a beam current of 4000 A was obtained at the Faraday cup.

When the plasma diode was replaced by a vacuum diode with an explosive needle-tip cathode, the acceleration mechanism was found to be similar, producing electron beam densities of  $10$  kA/cm<sup>2</sup> and maximum ion energies of 10 to 15 MeV for a breakdown voltage of 300 kV [129].

In a recent experiment with weakly relativistic electron beams, Plyutto employed the vacuum-spark plasma source in a cavity accelerator in which ions were accelerated by electrons with a-c, 6.3-MHz, 0.2- to 1-MV voltage applied to the accelerating gap through shorted quarter-wave coaxial resonator (Fig. 16).

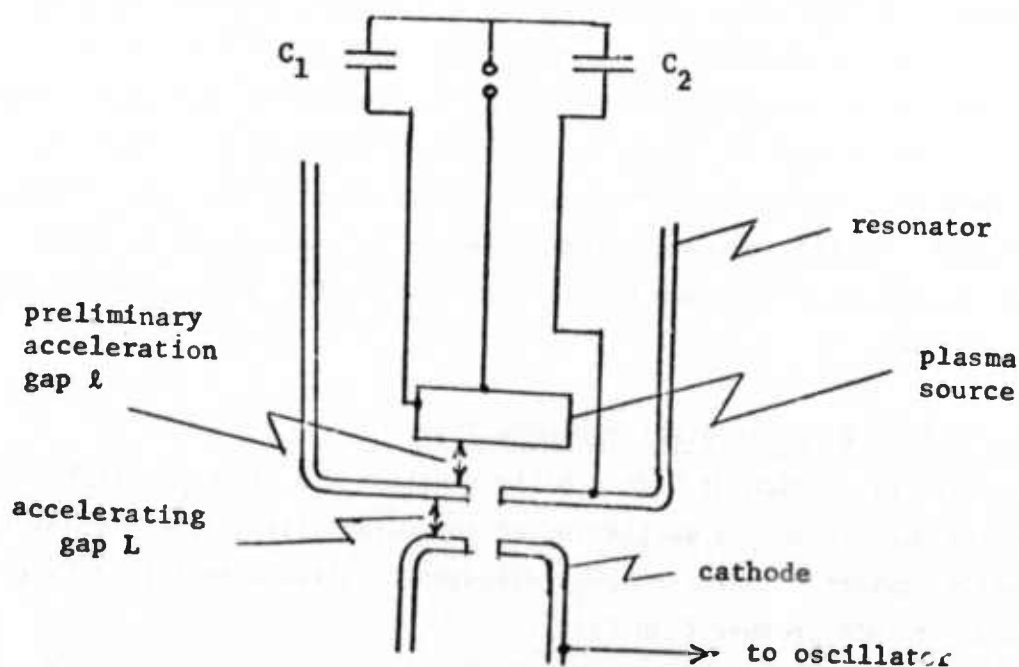


Fig. 16 -- Electron-ion acceleration system

The spark source was mounted axially near the bottom of the resonator and could be moved axially through a distance of  $\ell = 0$  to 40 mm, constituting a preliminary acceleration gap used in some experiments to increase acceleration effectiveness. The average current in the source was 3 to 5 kA at 1 MHz and a pulse length of 15  $\mu$ sec. When the accelerating voltage in the main gap reached a preassigned level, the spark source was triggered. The trigger timing was not synchronized with the oscillator [123].

For  $L = 2$  cm and resonator voltage of 0.25 MV, the observed proton energy was 2.5 to 3 MeV. The effectiveness of ion acceleration,  $k = E_{\text{max}}/eV$  (where  $E_{\text{max}}$  is maximum energy), thus was 10 to 12, or less than one-half of that obtained with nonrelativistic electron beams (see p. 84). Plyutto attributes this drop to the high frequency of the accelerating voltage and not to the increased velocity of the electron beam. The high-frequency effect becomes more pronounced with increasing  $L$ : for  $L = 4$  cm,  $k$  dropped to 4 to 6, and  $L = 7$  cm,  $k$  was 2 to 3. The preliminary acceleration gap  $\ell$  was used to improve the response of  $k$ . The capacitor bank  $C_2$  applied 30 to 60 kV to  $\ell$ , starting the acceleration process that further developed in  $L$ . This method changed the dependence of ion energy  $E_i$ , on the resonator voltage,  $V$ . For  $V = 0$ , the protons were accelerated in  $\ell$  to 0.5 MeV. When  $V$  increased in the range of 0.3 to 1 MeV, the ion energy increased faster than linearly with  $k = 7$  to 9. This improvement of  $k$  renders the resonators practicable in ion acceleration by electron beams [123]. However, for this purpose Plyutto prefers to use systems in which the gap is filled with plasma before the accelerating voltage is impressed on the gap.

#### D. THEORY OF THE ACCELERATING MECHANISM

The production of high-density electron and ion beams in Plyutto's scheme depends on the excitation of an instability in the form of the current cutoff. There are two necessary conditions that must be satisfied for this process [130, 131]:

1. The spark gap must first be filled with plasma whose parameters are such that during current rise plasma impedance becomes larger than the wave impedance of the circuit.
2. Critical current must pass through plasma, the current value depending on an initial voltage  $V_0$  for a given concentration of plasma.

These conditions produce an anomalous increase of plasma impedance leading to the cutoff of total current in the gap, and a rapid increase of potential difference across the gap up to a value frequently exceeding the initial voltage of the capacitor bank.

According to Plyutto, this amounts to a new method of forming electron and ion beams. The acceleration mechanism based on the collective interaction principle consists in general terms of the following stages [128]:

1. Plasma-field regime (plasma injected into electric field).
  - a. Extraction of electron current from plasma surface.
  - b. Increase of gap conductivity (shorting of gap).
  - c. Current cutoff.
  - d. Gap breakdown.
2. Plasma-current regime (electric field applied to plasma-filled gap).

There is no stage a; the process critical to ion acceleration occurs in stages b and c.

Fig. 17 shows typical values of current, voltage, and time intervals for the plasma-current regime. The phenomenological picture of this regime is shown in Fig. 18.

When the gap at zero field is being filled with plasma (a in Fig. 18), the algebraic sum of currents to the anode is zero. When a positive potential is applied to the anode (point 0 in Fig. 17), an electron-emitting plasma surface forms close to the anode. The previous equilibrium between the electronic and ionic components of the plasma flow is disturbed: The ion flow to the anode decreases and

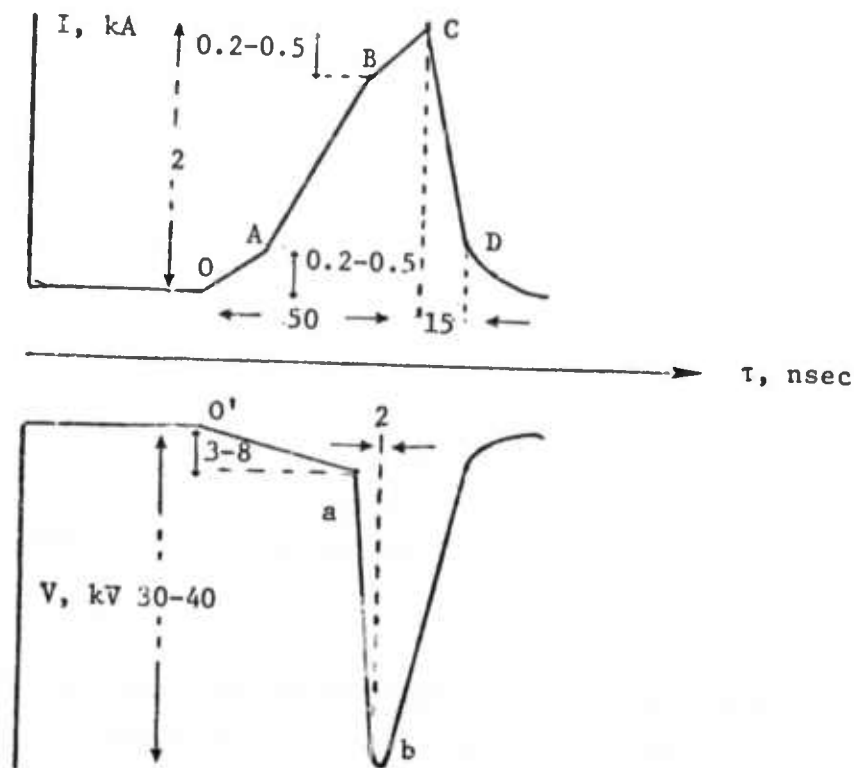


Fig. 17 -- Idealized total (anode) current voltage characteristic of the plasma-current regime [128]

cuts off altogether when  $V > kT_1/e$ , while the electron current increases. The concentration of ions at plasma surface grows with the increasing electric field and draws a part of the electron stream to neutralize the positive space charge maintained by the increasing field and by ions arriving from the plasma source (b in Fig. 18). This limits the electron current extracted by the anode and exerts a feedback effect on the operation of the plasma source itself: The output of electrons increases relative to the output of ions. The imbalance between the electron and ion flows generates a field within the plasma which accelerates some electrons, increasing the conductivity of the gap (point A in Fig. 17). We can assume that when point B in Fig. 17 is reached, all electrons are drawn into the continuous acceleration process.

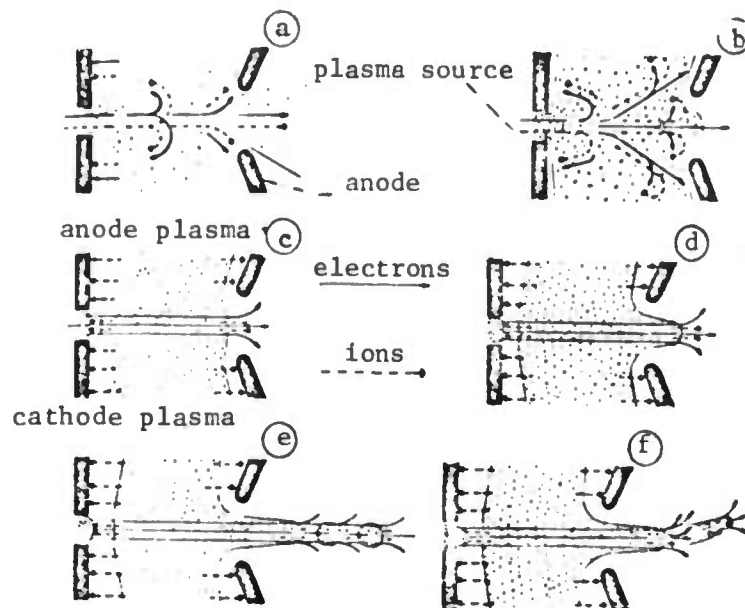


Fig. 18 -- Ion and electron currents in the gap during the several stages of the acceleration process of the plasma-current regime [128]

Shortly beyond point B, the plasma field increases faster, electron current reaches saturation, and the plasma source no longer emits ions. At this time, the localized plasma field shifts toward the cathode (or plasma source), there is a steep jump in gap potential (points a-b in Fig. 17), and a cutoff in the anode current (point D in Fig. 17). At the same time, the current in the electron beam passing through the anode aperture and measured by a Faraday cup increases 10 to 1000 times in 10 to 15 nsec.

The considerable increase in beam current density is attributed directly to the shift of the emissive plasma surface from the anode to the cathode [125, 128]. Thus, the plasma with increased density concentrated in the gap assumes the potential of the anode (anode plasma) and becomes the accelerating electrode, extracting electrons from an emissive surface that is now located at the spark-source aperture (cathode plasma). The extracted electrons form a beam which passes through the anode plasma (c in Fig. 18). In the short time interval

that the field is concentrated between two plasma surfaces (the plasma surface of the source opening and the anode plasma surface), the breakdown limitations do not hold, and field intensity can reach high values. The current between the two plasmas must be assumed to be bipolar. The ion component of the anode plasma neutralizes the space charge of the fast-electron beam, decreasing beam divergence. Beam pinching is evident to some degree.

This mechanism explains experimental data such as the high beam density, time dependence of current density, high electron energy, vaporization of the anode, and independence of beam direction from anode geometry [121, 127].

According to experimental data, the beam density on the axis reached 10 to 30 kA/cm<sup>2</sup>. The thickness  $x_0$  of the field between the cathode and anode plasmas can be computed by the 3/2 law for a bipolar stream and amounts to 0.3 mm. The field intensity forming the electron beam is of the order of  $10^6$  V/cm.

The formation of the electron beam is accompanied by an excess positive space charge in anode plasma, causing an additional flow of ions to the anode. This may be one of the causes of the current cutoff. Assuming that ion current density equals electron current density of  $\sim 160$  A/cm<sup>2</sup> in the saturation region (point C in Fig. 17), then for ion density in the gap of  $5 \times 10^{13}$  cm<sup>-3</sup> the necessary ion velocity is  $2 \times 10^7$  cm/sec, which is only slightly higher than the thermal velocity of protons of  $5 \times 10^6$  cm/sec.

The current cutoff can also be due to the expansion of the electric field between the anode and cathode plasmas caused by plasma decay and resulting in decreased density (and current) of the electron beam.

The plasma surface can be considered fixed during the beam formation period. Beyond the neutralization region, the beam's space charge induces an electric field at the plasma surface, with a fast drop in the direction of propagation. The maximum intensity of this field is 1.5 MV/cm for  $V_0 = 30$  kV and  $j_e = 30$  kA/cm<sup>2</sup>. This field accelerates nearby ions, causing the anode plasma to experience an axial pull through the anode aperture (d in Fig. 18). The field moves with the ions, so that part of the ions is constantly accelerated and reaches an energy exceeding



$eV_0$ . Field intensity decreases with diffusion of the ion bunch and decreasing electron beam current. As the ion bunch accelerates, it can divide (e in Fig. 18) or change direction through interaction with the electron beam (f in Fig. 18). It may be assumed that the maximum ion energy is proportional to the electron beam density [128].

The effectiveness of ion acceleration is measured by the ratio of maximum ion energy to the energy of the primary beam electrons:  $k = W_{\text{max}}/eV_0$ . In the early experiments [120],  $k = 20$  to  $30$ . In Plyutto's recent work with the resonant cavity accelerating system,  $k = 25$  to  $30$  in the unipolar regime and  $15$  to  $20$  in the alternating regime [123].

## VI. CONCLUSIONS

The foregoing account of the principal Soviet effort at developing high-current electron beams for technological applications leaves us with the task of assessing the results of this effort. Such an assessment is difficult for a number of reasons.

First, the current R&D work on accelerators and beams is still at too early a stage for us to draw any definite conclusions about the practical utility of high-current electron beams in any application outside scientific research. Furthermore, R&D work is still too distant from the point of conversion into the kind of operational hardware that is most readily comparable.

Second, the approach evident in the Soviet work differs considerably from that in the United States. Soviet research publications reveal a large and systematic theoretical effort to understand the physics of the beam-plasma interaction process and of intense electron beams. Theoretical analysis of neutralization, stability, and energy transfer takes up a major portion of the Soviet work, which also stresses the role of collective interaction mechanisms in these phenomena. Experimental work appears to be subordinate and performed mainly to verify the theoretical findings. The opposite situation seems to prevail in the United States. Here the research is largely experimental, and theoretical analysis is developed around specific questions arising from the experiment. One might say perhaps that, in a general sense, the Soviets are pursuing an inductive inquiry, whereas that of U.S. scientists is more deductive. Of course, there are exceptions: for example, the Hammer and Rostoker analysis of limiting currents is more like the Soviet theoretical approach, while Plyutto's experiments with plasma-filled gaps follow the American pattern.

A third reason for the difficulty of making an assessment is the perennial problem of incomplete information in Soviet open sources. While the publications on which this Report is based present a fairly comprehensive picture of the Soviet effort, it is by no means clear what proportion of the total effort these sources represent.

Particularly striking is the absence of large accelerators of the order of the Hermes, Gamble, and Aurora machines built in the United States some time ago. Their absence contrasts with the sophistication evident in much of the Soviet theoretical research, on the one hand, and with the resolution of the USSR Academy of Sciences to exert a maximum effort to build larger accelerators, on the other. Furthermore, the announced plans for the development of large machines, such as that of Rabinovich, fall by at least an order in scope below the current U.S. designs.

The contrast between an intensive theoretical base and a relatively weaker experimental base is a familiar feature of other areas of Soviet R&D. One possible inference, then, would be that the situation apparent in the area of high-current electron beams is not the result of a deliberate plan for systematic and orderly progression through all the early stages of research, nor is it due to the censorship of hardware information, but that it is merely a reflection of problems that typically afflict many sectors of Soviet technology. In such a situation, it is natural for the Soviets to pursue the inductive method, with its promise of a well-grounded general theory to start from, especially to the extent that they have an abundance of theoreticians and a ready access to Western experimental results.

The Soviets appear determined, nevertheless, to promote the development of high-current electron-beam technology. This is reflected in the discussions of the Presidium of the Academy of Sciences, USSR, concerning the responsibility for further development of *collective* acceleration techniques. There are two principal approaches to this problem. One consists of the collective acceleration of ions by means of compressed electron rings and is aimed primarily at applications in high-energy physics research. The work is being performed by the prestigious Joint Institute for Nuclear Research in Dubna under V. P. Sarantsev, Director of the New Acceleration Methods Department of the Institute. The other approach, based on high-current pulsed electron accelerators, is characteristic of the work of the research groups discussed in this Report. As we have seen, this approach has a technological orientation.

The Presidium of the Academy reviewed each approach in turn in 1971 and 1972. The achievements of the first approach were presented to the Presidium by Sarantsev, and those of the second by A. A. Kolomenskiy and M. S. Rabinovich of the Lebedev Physics Institute, and by Ya. B. Faynberg of the Khar'kov Physicotechnical Institute. The Presidium resolved that:

High-current pulsed electron accelerators should serve as the principal experimental base for the development of collective techniques. Maximum effort should be made to promote the construction of such accelerators. Along with the development and construction of specific systems and devices, the research should involve the basic problems of the physics of high-current relativistic beams and their formation, focusing, and interaction with various media [132].

Furthermore, the Presidium of the Academy requested that the Department of Nuclear Physics of the Academy, and thus presumably Sarantsev's Institute, provide broad assistance to the Lebedev Physics Institute and the Physicotechnical Institute. It appears, then, that the Academy of Sciences has placed the major emphasis on the approach represented by the Lebedev Physics Institute and the Physicotechnical Institute, which are engaged in linear high-energy pulsed development. It is this approach, rather than Sarantsev's, that offers the more immediate possibility of technological applications of high-current beams.

The other institutes and research groups discussed in this Report share this technologically promising approach to a varying extent. There is some overlap among these groups in theoretical methods and results, experimental techniques, and technological goals. Problems of current limits are being studied by Rukhadze and Rudakov, instabilities generated in the course of beam-plasma interaction are the center of attention of Rukhadze, Rudakov, and Faynberg, and the phenomena associated with plasma-filled diodes are being investigated by Rudakov and Plyutto. Rukhadze and Faynberg are also experimenting with the generation of microwaves and the pumping of lasers.

The Rukhadze group's research has the broadest range of potential technological applications, despite its preponderance of theoretical papers and relatively modest experimentation, at least as reflected

in the published material. A basic thrust of their work appears to be the attainment of the maximum possible current in the beam. This is directly relevant to the production of intense bursts of narrow-band microwaves, a goal that the Rukhadze group has been pursuing simultaneously in three media: plasma, vacuum, and solid state.

A similar objective is pursued by Faynberg, but limited to beam-plasma interaction. However, his approach in developing the technique of oscillation control by modulating the electron beam is unique. Depending on the type of instability and the frequency of the modulating signal, this technique appears capable of producing narrow-band pulses of rf energy at specified frequencies. It can also produce intense beams of ions.

The efficiencies of Rukhadze's and Faynberg's microwave oscillators, according to their published experimental results, are very low, not exceeding 1 percent. As of 1972, Faynberg's early expectations of 20 percent efficiency had yet to be realized.

Rukhadze stated in several of his research papers that the transmission of energy over long distances by means of a high-current electron beam is a prime research objective. Rukhadze is the only one among the four groups to refer to such a subject. He does not explain this idea in detail, nor does it appear in the formal lists of goals of the high-current electron beam research published in Rukhadze's reviews. Rukhadze places the long-distance energy transmission in the context of a beam drifting in a long plasma-filled metal waveguide. However, his analysis of the electric and magnetic neutralization of electron beams in plasma has shown that the degree of neutralization is not significantly different whether the beam drifts in unbounded homogeneous plasma or in plasma bounded by a metal waveguide. The context of this objective, therefore, may conceivably be extended by Rukhadze to the passage of the beam through the atmosphere, although he does not discuss this in his publications. The interaction of high-current electron beams with the atmosphere is the subject of Rukhadze's ionospheric studies. The interesting aspect of this is the extremely long pulse requirement (1 sec) which, even with the moderate currents (1 A) proposed by Rukhadze, would deliver enormous energies.



The scope of the work of the Rudakov and Plyutto groups is much narrower. Rudakov's research is significant because of his intensive theoretical treatment of beam-plasma interaction, considered from the viewpoint of instability excitation as a means of energy transfer from the electron beam to the plasma. His experimental work with the Neptun machine is of interest, because it is aimed at the experimental verification of the neutralization theories and at the behavior of electron beams in atmospheric air. The bulk of his work, however, appears directed toward the application of electron beams to the heating of plasma for CTR purposes, and for this reason, it is difficult to determine the precise purpose of Rudakov's work.

Plyutto has emerged as a significant and promising experimentalist whose work with plasma-filled diodes gave the first clear evidence of the collective acceleration mechanism in linear electron beams. The techniques that Plyutto is developing may offer the best solution to the problem of producing higher currents and energies in electron and ion beams. Plyutto's group appears to be much smaller and less important than the other three groups reviewed here, and Plyutto and his team may perhaps be regarded as fringe members of the Soviet high-current accelerator community. Nevertheless, a great deal of attention is paid to their work by the key researchers of that community, including Zavoyev, Sagdeyev, Faynberg, Sarantsev, and Budker, and such attention is a strong indication of the Plyutto group's relevance to the goals pursued by all.

The real size of the Soviet effort relative to that of the U.S. is of course impossible to determine solely on the basis of the open-source literature. Nevertheless, a comparison of the segment of the Soviet effort reflected in this literature with the corresponding U.S. segment may have a limited value in sharpening our perception of the activities of the two countries in this area. Thus the size of the effort represented by the four Soviet groups discussed here, in terms of the number of active authors, is roughly equal to that of the U.S. effort in this field. The four Soviet groups, however, represent only about one-half of the total Soviet activity in the study and application of high-current



high-energy particle beams. Furthermore, a significant portion of the published Soviet effort has been in evidence for at least 10 years, while the published U.S. effort was rather small before 1971.

The Soviet effort appears much more coordinated than its U.S. counterpart -- a conclusion that may possibly be affected by our methods of analyzing the information available to us. Nevertheless, there are significant indications that the conclusion is valid. The Soviet research groups are fewer in number, but larger in size. There is some degree of division of labor, especially between the Soviet Western and Siberian groups; the former appear to stress the theory and application of the beam-plasma interaction process, while the latter place a heavier emphasis on the accelerator design. There is also considerable inter-group supervisory coordination, whereby key researchers from one group review the work and consult with the members of other groups.

In the United States, there is more mobility of individual researchers among the different groups, but little, if any, coordination of the overall research effort. The two largest U.S. efforts, as reflected in the subject matter of papers read at the annual meetings of the American Physical Society and the affiliations of their authors, are beam and plasma dynamics and plasma heating for controlled-fusion purposes. Both subjects appear to be treated at a higher effort level in the Soviet Union than in the United States, according to such indicators as the duration of research, the number of contributing authors, the extent of systematic analysis accorded to the various aspects of the problem, and the range of such topics. The Soviet treatment of electron-beam-driven microinstabilities in plasma, instability control, modulation of the electron beam, and neutralization problems is particularly impressive. The preponderance of the Soviet research effort exists also in the area of microwave generation, where the Soviet groups have launched a broadly based attack on problems involving gaseous plasma, solid-state plasma, and vacuum.

Only in the area of laser pumping by relativistic electron beams and pellet fusion involving such beams does the United States appear to have a research program on a par with or more extensive than that of the Soviet Union.

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